Electrical Engineering

October 1941

We are happy to report

PROGRESS

ALSIMAG has been made in the largest, best equipped steatite insulator plant in this country. Declining Government financial aid, this plant is now being expanded to provide a 300% increase in capacity.

Careful plans of more than a year swiftly bear fruit. As walls go up, they are literally built around the newest and most modern equipment. Trained men take charge. The pace of production whirls steadily upward, 24 hours a day—7 days a week.

This new plant is of glass block, brick and reinforced concrete. Large areas of it are air conditioned, all of it has the complete dust controls essential to highest quality manufacture. Wherever possible, automatic control units are a part of all equipment.

Defense requirements have the right of way in this plant. Neither you, nor we, would have it otherwise. Daily we come nearer our goal of being able to supply defense requirements and your requirements. We believe the day is close at hand when once more we will be able to care for your needs with the speed and competence that won us so many friends throughout the nation.

The cornerstone of this organization is a policy of continued improvement through research and development. The Engineering and Production Staffs of American Lava Corporation contain representatives of many of the leading technological institutions of this country. Thus it is only natural that four completely equipped new laboratories sweep across one floor of this new building. These four laboratories, electrical, chemical, mechanical and testing, are in charge of men whose skill is favorably known to leading engineers in this country and abroad. They are ready to work for you on any problem involving technical ceramics.

39th Year of Ceramic Leadership

ALSIMAG

Trade Mark Reg. U.S. Pat. Off.

FROM CERAMIC HEADQUARTERS

AMERICAN LAVA CORPORATION • CHATTANOOGA • TENNESSEE

CHICAGO • CLEVELAND • NEW YORK • ST. LOUIS • LOS ANGELES • SAN FRANCISCO • BOSTON • PHILADELPHIA • WASHINGTON D. C.

Portable Megohmmeter *with a* Resistance Range *of* TWENTY MILLION TO ONE

TO MEET the need for a portable, d-c operated megohmmeter similar to the older Type 487-A Megohmmeter developed some time ago, G-R announces the Type 729-A instrument. This meter retains the basic circuit features of the a-c meter, but incorporates a number of improvements which increase its stability, its range and its compactness. The new meter is particularly suited to measurements of moisture content of various materials by the conductivity method where extremely wide resistance ranges must be covered.

FEATURES

●**WIDE RANGE**—2,000 ohms to 50,000 megohms, in 5 overlapping steps.

●**IMPROVED STABILITY**—highest-value resistance standard sealed in vacuum and coated to prevent surface leakage; greatly increases stability on the high range.

●**COMPACT**—weighs only 8¾ pounds; dimensions: 11 x 6⅝ x 5⅞ inches.

●**IMPROVED CIRCUIT**—battery placed in measuring loop without any controlling resistances; low-resistance limit determined by internal resistance of battery.

●**GOOD ACCURACY**—within 2% from 30,000 to 300,000 ohms; within 5% from 300,000 ohms to 3,000 megohms; decreases to about 10% at 10,000 megohms.

●**CONVENIENCES**—zero adjustment automatically corrects sensitivity to insure correct readings throughout life of batteries; instrument is automatically turned off when cover is closed.

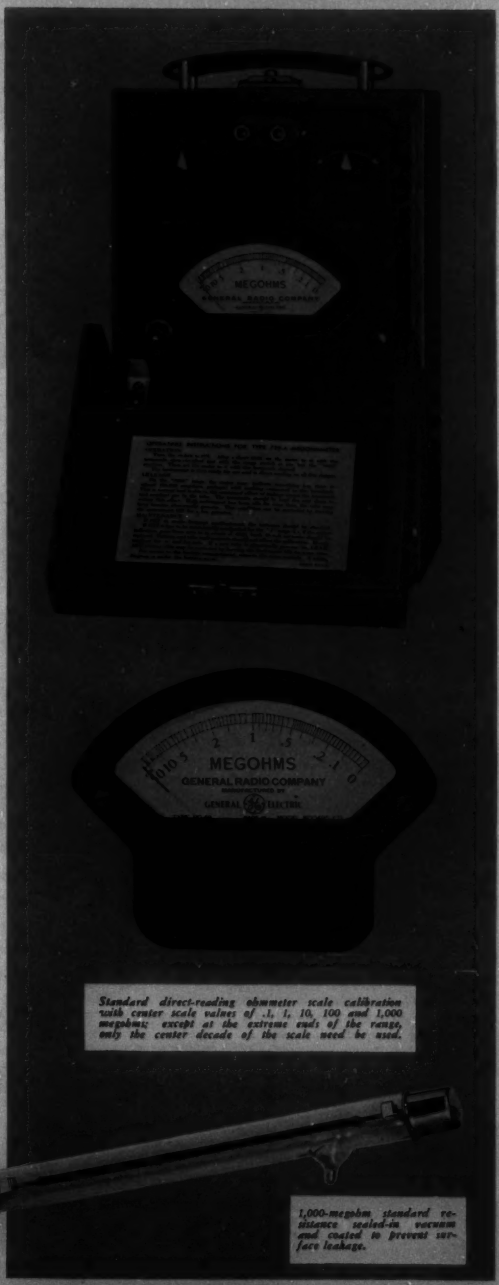
●**LOW VOLTAGE ON UNKNOWN**—does not exceed 22½ volts and varies with meter reading.

Type 729-A MEGOHMMETER (complete with tube and batteries)....$85.00

WRITE FOR BULLETIN 740 FOR COMPLETE INFORMATION

GENERAL RADIO CO.

CAMBRIDGE, MASSACHUSETTS



Standard direct-reading ohmmeter scale calibration with center scale values of .1, 1, 10, 100 and 1,000 megohms; except at the extreme ends of the range, only the center decade of the scale need be used.

1,000-megohm standard resistance sealed-in vacuum and coated to prevent surface leakage.

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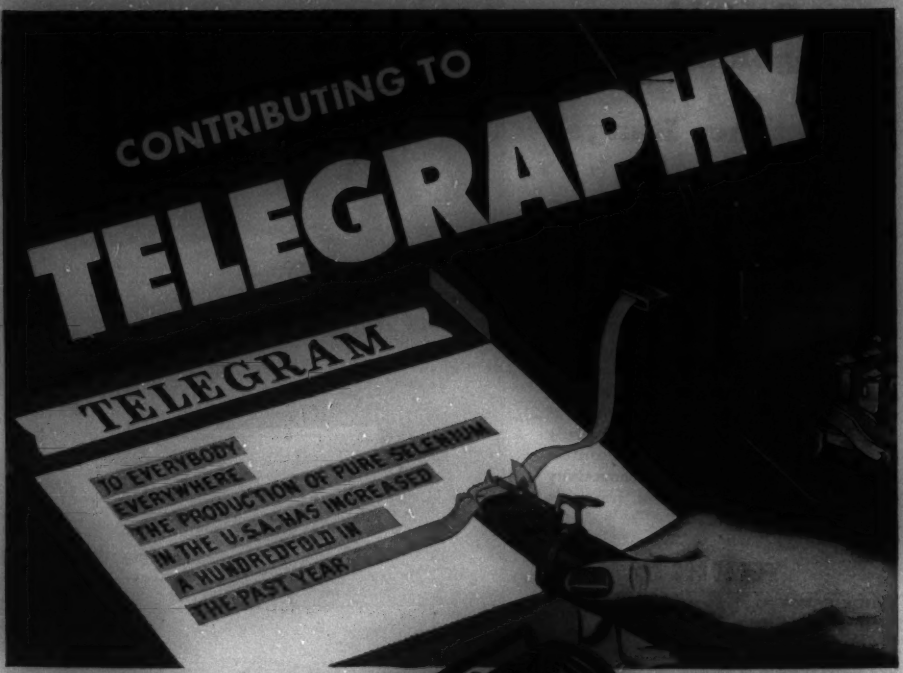
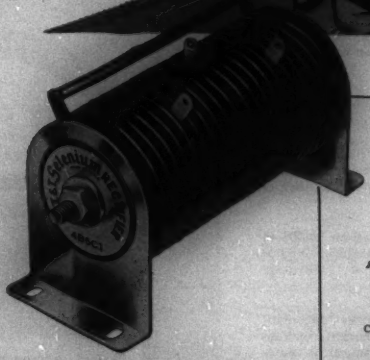


Telegraph engineers, extremely exacting in their requirements, have been quick to discover in the I. T. & T. Selenium Rectifier a ready adaptability to the many demands of Telegraphy, oldest of all the electrical communication arts, for direct current from alternating current sources.

Among the many outstanding features of Selenium Rectifier in its application to Telegraphy are: good regulation for keyed loads . . . compact, small size and light weight which minimize space requirements . . . extremely wide ambient temperature range which makes it ideal for field use under all conditions . . . adaptability to closely regulated currents . . . stable output and long life . . . assured high efficiency of operation and low standby losses.



Because it is entirely metallic in construction and has no moving parts, the I. T. & T. Selenium Rectifier once installed requires no maintenance—a feature of particular value to telegraph field engineers.

I. T. & T. Selenium Rectifiers are Completely Produced from American Material.
Consulting engineering services available for specific requirements.
Address Technical Department for descriptive bulletin.

AMONG OUR CUSTOMERS

U. S. Army
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Tropical Radio Company
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World Wide Communications

INTERNATIONAL TELEPHONE DEVELOPMENT CO., INC.
137 Varick Street, New York, N. Y.

Gulf USED OKONITE

For this SUBMARINE "DIVINING ROD"

Exact gravity measurements to help locate oil deposits can be made at depths of several hundred feet below water by means of this underwater gravimeter, developed by the engineers of Gulf Research and Development Company.

The electric devices, by which operations are controlled and recorded, include motor operated leveling devices and indicators, light sources for film recording, a motor-operated camera and an alarm system, all within the instrument itself and a control unit containing seven meters, four pilot lights, nine switches, two relays and two motor-driven contactors.

All of these electric circuits are contained in a single Okonite Cable, one inch in diameter, containing 19 conductors. The insulation of each conductor is color coded and the entire assembly is reinforced with 4/64" Okocord rubber over strong mesh braid, which is in turn covered with an outer jacket of Okoprene, containing 60% neoprene, vulcanized to the rubber jacket to form a water- and air-tight bonded protective sheath, resistant to water, air and sunlight.

Designed by Okonite Engineering Service and specially built for the job, this cable represents an example of the kind of problems which our organization is particularly well equipped to handle. Okonite engineers are always ready to consult on any wire or cable problem.

THE OKONITE COMPANY, Passaic, N. J.

Offices in Principal Cities

OKONITE OKONITE

NO. 7

ALUMINUM, DEFENSE, AND YOU

THE TIMETABLE OF ALUMINUM FOR DEFENSE

up to September 10, 1941

1938

1938 Sept. *Munich.*

Oct. *Czechoslovakia invaded.*

Nov. Alcoa inaugurates $26,000,000 expansion program.

Dec. Alcoa produced 287 million pounds in 1938; had more than a year's supply on hand.

1939

1939 Jan. New extrusion and tube mill begins operation at Lafayette, Ind.

Feb. Start building an excess stock pile of airplane sheet.

Mar. *Bohemia and Moravia occupied.*

Apr. *Albania invaded; Congress authorizes Army to acquire 6,000 planes by July, '41, and Navy 3,000 by '44. Aluminum for all these would take about two months 1941 production.*

Sept. *Poland invaded; U. S. Neutrality proclaimed; limited National emergency proclaimed.*

Alcoa authorizes new metal-producing capacity at Alcoa, Tenn.

Nov. *Finland invaded; Cash-and-carry act signed.*

Alcoa completes $26,000,000 expansion program, begins plans for a larger one.

Dec. *U. S. protests blockade of German exports.*

New metal-producing plant authorized at Vancouver, Wash.

1939 production 327 million pounds; 215 million on hand.

1940

1940 Jan. *First request for defense appropriation in Budget Message.*

Alcoa announces $30,000,000 more plant expansion.

Mar. Alcoa reduces price of aluminum from 20c to 19c, starts construction of Vancouver, Wash., plant.

Apr. *Denmark and Norway invaded.*

May *Low countries invaded; National Defense Advisory Commission named.*

New metal-producing unit begins operation at Alcoa, Tenn.

June *Dunkerque; France capitulates.*

Additional metal-producing unit authorized at Alcoa, Tenn.

July *Congress lifts previous limits on numbers of planes.*

Aug. *Air offensive against England begins; 50 destroyers exchanged for island air bases.*

Alcoa reduces price of aluminum ingot from 19c to 18c; capacity for making alumina increased.

Sept. *Egypt invaded; Selective Service Bill passed.*

First metal manufactured at Vancouver, Wash., plant and new units for additional capacity authorized.

Oct. *Rumania invaded.*

Alcoa authorizes another $150,000,000 for expansion.

Nov. *26 bombers on contract turned over to Britain.*

Alcoa reduces ingot price from 18c to 17c; additional capacity authorized at Badin.

Dec. Alcoa 1940 production 413 million pounds; 154 million on hand.

1941

1941 Jan. *OPM established; NDAC says aluminum supply adequate to meet October, 1940, estimates of requirements.*

Alcoa authorizes additional capacity at Alcoa, Tenn.

Feb. *Aluminum put on priorities.*

Mar. *Lend-lease bill signed.*

Alcoa produces 44,000,000 pounds of metal this month.

Apr. *Yugoslavia invaded; U. S. occupies Greenland.*

May 150 million-pound-annual-capacity plant at Vancouver, Wash., completed and operating at capacity.

June *Crete lost; Russia invaded.*

July *New Government aluminum plants authorized; U. S. occupies Iceland; Japan moves into Indo-China.*

Alcoa produces 53,000,000 pounds this month; Badin unit authorized November, 1940 starts operation.

Aug. *U. S. Government announces Aluminum Company of America will build and operate 3 Government-owned aluminum smelting plants and one for making alumina.*

Alcoa announces ingot price reduction to 15c, effective October 1, 1941.

Alcoa and T. V. A. conclude agreement to unify two great hydro-electric power systems in the Tennessee Valley, which will add at least 200,000,000 pounds to America's annual aluminum producing capacity.

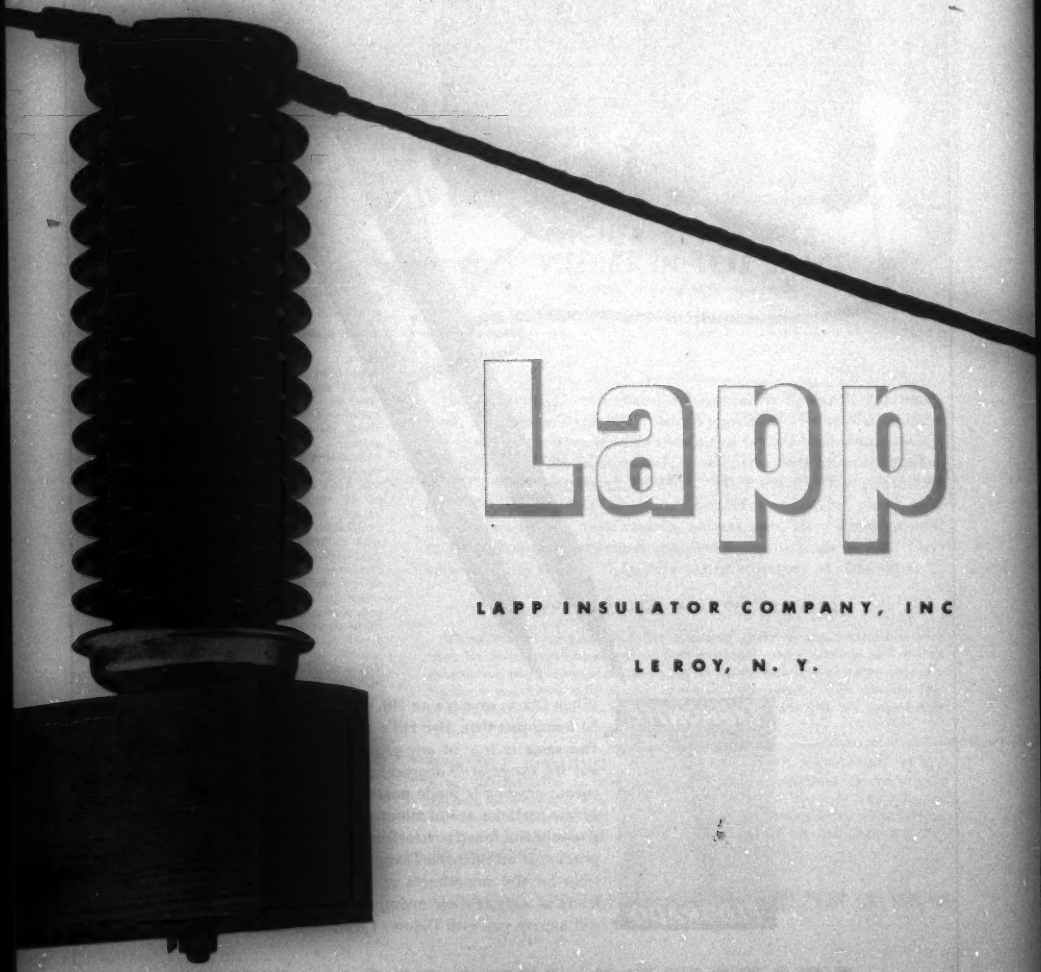
Alcoa produces 54,000,000 pounds of aluminum this month.

Sept. Sites selected for one of the Government-owned aluminum plants and for the alumina plant; railroad, water, and sewage facilities provided; construction contracts being executed.

Excess stock pile of aluminum airplane sheet started in February, 1939, being maintained at 5,000,000 pounds.

ALUMINUM COMPANY OF AMERICA

You can meet many demands for increased load by converting existing lines to higher voltages. The Lapp Line Post offers a means of doing this job quickly, economically—and getting top performance.



Lapp

LAPP INSULATOR COMPANY, INC

LE ROY, N. Y.

Want to see *two* sets of *identical* twins?

When Dixon says it's an HB, you can depend on its being just that. Two HB's are identical twins. The same is true of any given degree throughout the range of 17 degrees. Such uniformly accurate grading is made possible by *Typhonite*—whose particles are of minutely even, controlled size—the size found best for lead making. *Typhonite*, product of an exclusive Dixon process, is responsible for the smoothness of *Typhonite* Eldorado leads as well as their opaque lines. Your dealer will supply you with Dixon's *Typhonite* Eldorado.

PENCIL SALES DEPARTMENT 42-J10, JOSEPH DIXON CRUCIBLE COMPANY, JERSEY CITY, N. J.

Again! KOOLOHMS LEAD THE WAY

with two long-awaited improvements

✔ METER MULTIPLIERS THAT WITHSTAND 150°C

✔ HIGHER RESISTANCE VALUES IN LESS SPACE

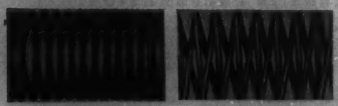
(Example: 4 megohms in Type MFB)

THIS CONSTRUCTION REVOLUTIONIZED WIRE WOUND RESISTOR DESIGN

Resistance wire touches but cannot short

Engineers will be quick to appreciate the many advantages made possible in wire wound resistor construction by the exclusive Koolohm process of insulating the wire itself *before it is wound*. This permits layer windings for higher resistance in less space; progressive windings for non-inductive resistors that are truly non-inductive even at 50 to 100 Mc.; larger wire sizes; faster heat dissipation; greater stability; extreme accuracy and greater humidity protection. No secondary insulations such as brittle cements or enamels are needed on the windings. For double protection, however, most Koolohm types are encased in a sturdy outer ceramic shell that will not peel or chip and allows for mounting directly to metal parts. Koolohms are made in a full line of shapes, types and sizes for all needs. Write for the new edition of the Koolohm Catalog, just out.

Koolohm wire with section of ceramic insulation removed.



Single layer winding — Progressive winding

In conformity with standard Koolohm Resistor construction, these new Type MFA and Type MFB Meter Multipliers are made with wire that is insulated *before it is wound* with a tough, 1000° C. heat-proof, moisture-proof ceramic material (U. S. Patent No. 2,213,969). They are further protected by a Pyrex glass high-voltage insulator tube, 1/8" thick and heat-treated. By test and in actual use, they have proved their ability to withstand temperatures as high as 150° C.—considerably higher than any other resistors of this type.

APPROVED FOR NATIONAL DEFENSE

These units are approved for exacting defense applications where they have set new standards of performance under adverse salt water immersion conditions. Complete information gladly sent upon request. Sprague engineers will gladly cooperate in helping you choose the proper Koolohm for greater dependability, longer life on practically any wire wound resistor application.

Type MFA KOOLOHM (9 13/16" long) is available in resistance ratings of 3.5, 4.0, 4.5, 5.0 and 6.0 megohms, with voltage ratings of 3.5, 4.0, 4.5, 5.0 and 6.0 KV respectively.

Type MFB KOOLOHM (5 5/16" long) is available in resistance ratings of 1.0, 1.5, 2.0, 2.5, 3.0, 3.5 and 4 megohms, with voltage ratings of 1.0, 1.5, 2.0, 2.5, 3.0, 3.5 and 4 KV.

SPRAGUE SPECIALTIES CO. • RESISTOR DIVISION
North Adams, Mass.

SPRAGUE KOOLOHM RESISTORS

Greatest Improvement in Wire Wound Resistor Construction in 20 Years

THE Standards of the American Institute of Electrical Engineers now comprise fifty sections on electrical machinery and apparatus. They are chiefly devoted to defining terms, conditions, and limits which characterize behavior, with special reference to acceptance tests, and many of them are recognized officially as American Standards.

The Standards available are listed below, together with prices. A discount of 50%, on single copies only, is allowed to Institute members (except on Nos. C57.1, 2, 3, and C37.4). Such discount is not applicable on extra copies unless ordered for other members. Numbers of the Standards Sections should be given when ordering. A binder (illustrated above) for standards is available with durable, stiff covers, resembling leather, lettered in gold. Price, $1.75 net.

AIEE STANDARDS

(Figures in Parentheses Give Dates of Latest Editions)

No. 1	General Principles Upon Which Temperature Limits Are Based in the Rating of Electrical Machinery (6-40)	$0.40
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**11	Railway Motors (3-37)	.50
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C57.2	Test Code for Transformers, Regulators and Reactors (1940)	
C57.3	Guides for Operation of Transformers (1940) (C57.1, C57.2, C57.3, published as one booklet supersede A.I.E.E. Nos. 12, 13, 14, 100 and Test Code for Transformers. The member discount does not apply on price of this publication which is 75 cents net.)	.75
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*17g1	Letter Symbols for Electrical Quantities (11-28)	.20
17g1A	Letter Symbols for Electric and Magnetic Quantities	
**17g2	Graphical Symbols for Electric Power and Wiring (1-34)	.20
**17g3	Graphical Symbols for Radio (1-34)	.20
**17g5	Graphical Symbols for Electric Traction Including Railway Signaling (1-34)	.40
**17g6	Graphical Symbols for Telephone and Telegraph Use (3-29)	.20
*18	Capacitors (6-34)	.20
19	Oil Circuit Breakers (4-38)	.40
C37.4	A-C Power Circuit Breakers (1-41) (A proposed revision of No. 19. The member discount does not apply on price of this publication which is 60 cents net.)	.60
20	Air Circuit Breakers (5-30)	.30
22	Air Switches and Bus Supports (6-40)	.40
*C37.1(23)	Relays Associated with Power Switchgear (1937)	.40
*C37.2(26)	Automatic Stations (1937)	.40
27	Switchboards and Switching Equipment for Power and Light (10-30)	.30
27A	Switchgear Assemblies (2-41) (A proposed revision of No. 27. No charge.)	
*28	Lightning Arresters (3-36)	.30
*30	Wires and Cables (4-37)	.40
*C39.1(33)	Electrical Indicating Instruments (7-38)	.40
*36	Storage Batteries (2-28)	.20
*38	Electric Arc Welding Apparatus (1-34)	.40
*39	Electric Resistance Welding Apparatus (1-34)	.30
*41	Insulator Tests (3-30)	.30
41A	Insulator Tests (3-41) (A proposed revision of No. 41. No charge)	
45	Recommended Practice for Electrical Installations on Shipboard (7-40)	1.50
*46	Hard Drawn Aluminum Conductors (6-27)	.20
*C8.5	Specifications for Cotton Covered Round Copper Magnet Wire. (See C8.7 for price.)	
*C8.6	Specifications for Silk Covered Round Copper Magnet Wire. (See C8.7 for price.)	
*C8.7	Specifications for Enameled Round Copper Magnet Wire. (C8.5, 8.6 and 8.7 published as one pamphlet) (1936)	.30
**C8.11	Code Rubber Insulation for Wire and Cable for General Purposes (1936)	.20
**C8.12	Cotton Braid for Insulated Wire and Cable for General Purposes (1935)	.20
**C8.16	Tree Wire Coverings (1936)	.20
**C8.17	Class AO 30 Per Cent Rubber Insulation for Wire and Cable for General Purposes (1936)	.20
**C8.18	Weather Resistant Wire and Cable URC Type (1936)	.20
*C8.19	Weather Resistant Saturants and Finishes for Aerial Rubber Insulated Wire and Cable (1939)	.20
*C8.20	Heavy Wall Enameled Round Copper Magnet Wire (1939)	.20
**72	Specifications for Weatherproof Wires and Cables. (See No. 73 for price.)	
**73	Specifications for Heat-Resisting Wires and Cables. (Nos. 72 and 73 published as one pamphlet) (9-32)	.20
500	Test Code for Polyphase Induction Machines (8-37)	.50
501	Test Code for D-C Machines (7-41)	.50
520	Test Code for Apparatus Noise Measurement (3-39)	.30
	Total Cost of Complete Set	$15.85

* *Approved as American Standard*

** *Approved as American Tentative Standard*

SECTIONS IN PREPARATION

Seven such sections are now available in report form for purpose of criticism, and copies will be sent without charge upon request. These sections are as follows:

No. 6	Mercury Arc Rectifiers.	25	Fuses Above 600 Volts. (7-41)
21	Apparatus Bushings (3-41) (Including Test Code)	40	Electrical Recording Instruments.
24	Protector Tubes	—	Test Code for Synchronous Machines.

American Institute of Electrical Engineers 33 West 39th Street New York

Quickest Way TO PROVIDE

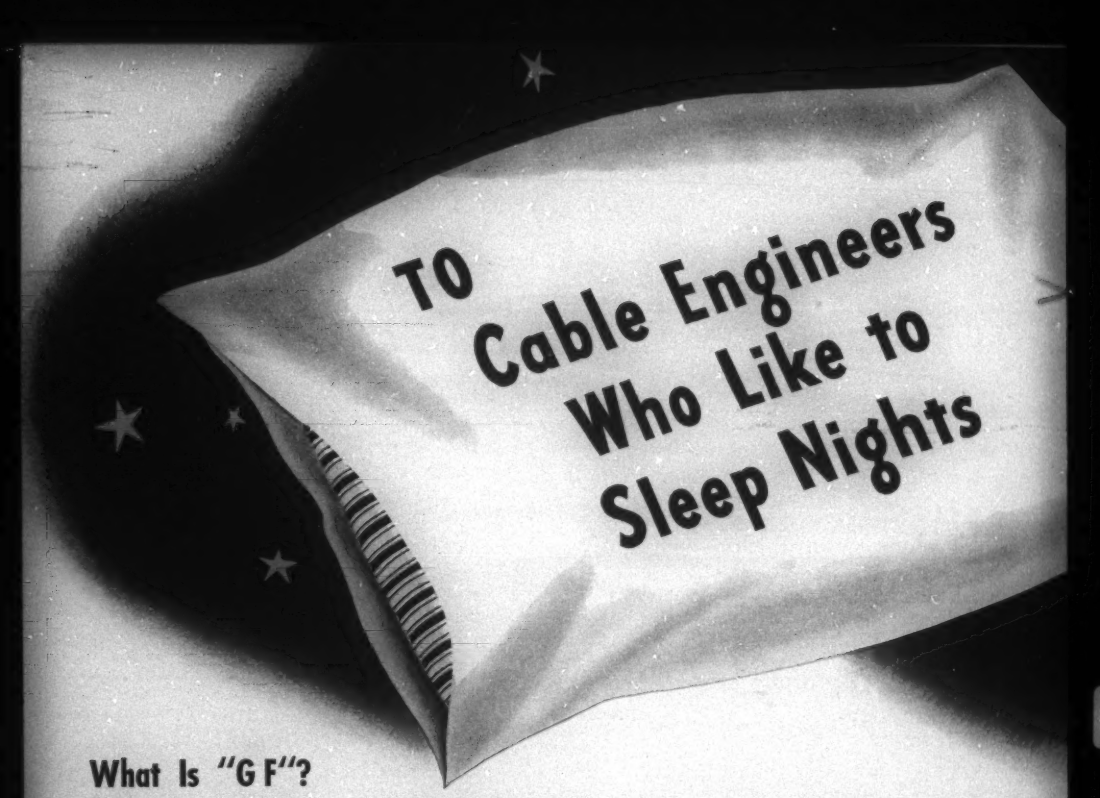
FOR MORE LOAD ON YOUR SYSTEM—AT LOWEST COST, TOO!

MANY distribution engineers are finding that they can supply the present imperative power demands of their industrial customers—without a change in system layout—just by installing Pyranol capacitors on feeders. By neutralizing reactive kva, capacitors release valuable system capacity—amounts ranging from 1/3 to 2/3 kva for each kva of capacitors installed.

Cost? Very low in terms of what they accomplish—on many actual feeders, $7 per kva installed. Get details from our local representative, Ask for Bulletin GEA-3333. General Electric, Schenectady, N. Y.

PYRANOL CAPACITORS
THEIR STABLE CHARACTERISTICS ASSURE LONG LIFE

GENERAL ELECTRIC



What Is "G F"?

THIS is a brand new cable—low-pressure, gas-filled—for 10- to 40-kv service. It is comparable, in general construction and economy, with solid-type paper-insulated cable and has the added advantage of self-supervision.

Experience with installations of this new cable totaling 140,000 feet has proved its advantages for important transmission and distribution feeders where continuity of service is of vital importance. These installations have also demonstrated that it is ideal for cable lines over routes where the profile is rugged and migration of compound in the conventional type of cable has given trouble.

Self-supervising Feature

By maintaining inert gas within the cable, self-supervision is provided. That is—any break in the sheath* causes a slight loss of gas, and this loss, on account of lowered pressure, shows up promptly through an automatic alarm relay at the station. Then repairs can be made in time to avoid service failure. In most cases, if a leak occurs it is small, and additional gas can be fed to the cable in case you wish to postpone repairs.

In other words, when a leak in the cable sheath occurs, the internal gas pressure prevents entrance of moisture or oxygen and at the same time gives an alarm. Failure of the cable is thus prevented, and the leak can be readily located and repaired. Leaks in the sheath of conventional solid-type paper-insulated cable almost always result in service failures, because you have no warning or opportunity to make repairs.

Profile Presents No Problem

By use of dry, low-pressure nitrogen and a simple, effective means of distributing gas throughout the cable, positive pressure is maintained regardless of profile—and without requiring any manhole auxiliary equipment. The system has worked perfectly on 5000- to 16,000-foot installations over a period of years. These included 200-foot riser lengths—a tough job for the previous type of cable used.

Easy to Install

The necessary joints, terminals, and pressure relays have been developed. The method of placing this cable into service is in no essential respect different from those familiar to cable engineers.

More complete details are yours upon request. Ask the G-E office near you for Bulletin GEA-3652. General Electric Company, Schenectady, New York.

It is reported to us that approximately 85 per cent of cable failures are from external causes, i.e., not an inherent fault of the cable.

HERE'S OUR NEW SELF-SUPERVISING CABLE

We Call It "GF" . . . It's GAS FILLED

Self-supervision—prompt indication if a leak occurs
Costly failures and interruptions minimized
More uniform quality of insulation

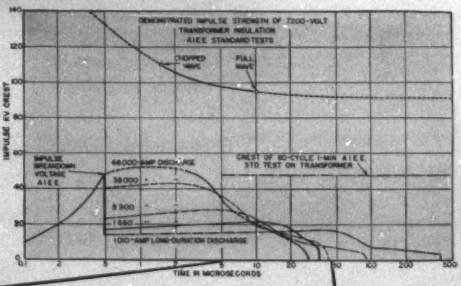
Less space required—more power for a given duct size
Low installation and maintenance cost
Profile presents no problem

GENERAL ELECTRIC

You Get A Big
EXTRA MARGIN OF PROTECTION
with MODERN Pellet Arresters

Even with severe lightning discharges, pellet arresters limit stresses to less than half the impulse test strength of the distribution transformer

HERE'S PROOF OF THAT EXTRA MARGIN OF SAFETY. . .



In this graph, the impulse volt-time oscillograms of the 9-kv pellet arrester are compared with the volt-time impulse test strength of a 7200-volt distribution transformer

. . . AND YOU ALSO GET EXTRA LARGE DISCHARGE CAPACITY

Pellet arresters mounted separately (above) or directly on transformer (left) withstand severe lightning strokes. Pellet arresters have discharge capacity in excess of the highest lightning discharge currents measured on distribution circuits.*

*See "*Discharge Currents in Distribution Arresters*," Electrical Engineering, June, 1938.

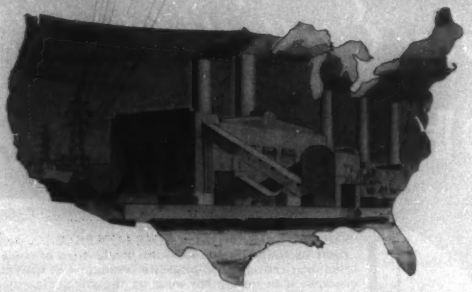
The Extra Values in Pellet Arrester Protection

1. You avoid repeated stresses close to the transformer strength.
2. You have plenty of margin of protection, even assuming considerable depreciation of transformer insulation with years of service.
3. You get excellent protection for your old transformers as well as for new ones.
4. You can expect the maximum life from your transformers.

NO NEED TO GAMBLE . . . ***Get the important extra margin of protection for your distribution transformers by specifying G-E pellet arresters. Select them from Bulletin GEA-2975. General Electric Company, Schenectady, N. Y.***

GENERAL ELECTRIC

Essential to Defense



An Adequate and Continuous Supply of Electric Power stands high among the Essentials for Defense Production

The defense program races against time, calling on electric power, men, and raw materials. And electric power gets in the race only when it is brought to its point of use through the electrical conductors on our transmission and distribution systems.

Obviously necessary is the power supply to plants working directly on armaments. No less necessary is the power for all industry backing our armament makers with tools, equipment, and materials. And for efficient continuous production, our transportation and communication systems must operate, cities must be lighted, workers' homes must be served with electricity and all the essential services powered by electricity must be maintained.

The use of Copperweld and Copperweld-Copper Conductors conserves the copper metal needed for defense production. The steel core of Copperweld supplies mechanical strength so copper need only do the job it does best—conduct electricity.

COPPERWELD AND COPP[illegible]CTORS CONSERVE COPPER

COPPERWELD STEEL COMPANY
GLASSPORT, PENNSYLVANIA

Three Good Reasons

why Engineers choose

OHMITE RHEOSTATS

1 SMOOTH, GRADUAL, CLOSE CONTROL . . . permanently built-in and proved right in countless installations. Every turn of wire is a separate resistance step. Self-lubricating metal-graphite contact, with universal mounting, insures perfect contact with negligible wear on the wire. This means smooth electrical control unequalled in power rheostats.

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Electrical Engineering

Registered U. S. Patent Office

for October 1941—

The Cover: A 10,000-kva 33/115-kv power transformer being installed on the system of the Public Service Company of New Hampshire

Photo by L. McKenney, General Electric Company, Boston, Mass

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High Lights • •

Double-Fed Asynchronous Machine. An attempt has been made to derive formulas for the damping and synchronizing torques of the double-fed asynchronous machine, which has become important as a drive with wide speed range. The total system consists of mechanical springs, electrical "springs" (synchronizing torques), mechanical dampings, electrical dampings, and masses; dynamic stability of the system depends upon the springs, dampings, and masses of all its parts (*Transactions pages 923–4*).

National Defense. Continuing the policy of calling attention to some of the significant developments in national defense, news reports on growing shortages of minerals and metals; curtailed use of "critical" materials; the safety campaign to aid defense; OPM's "training within industry" program; discussions of education and defense at a recent conference of educators and defense officials; and others appear in the section "Of Current Interest" (*pages 509–13*).

Excitation of Ignitron Rectifiers. Experience with the variety of circuits that may be used to excite ignitron rectifiers has resulted in the development of separate excitation systems which use either rotating impulse generators, or capacitor impulses controlled by thyratrons, or by saturating reactors; the last system is positive and has no parts requiring frequent renewal (*Transactions pages 943–8*).

Current-Transformer Calculations. A simplified method for calculating the performance of current transformers depends upon three fundamental constants: open-circuit saturation; secondary-coil resistance; and equivalent leakage reactance. Curves have been plotted which allow direct reading of the components of exciting current that cause ratio error and phase angle (*Transactions pages 949–54*).

Lightning Phenomena. In the last of the series of three articles reviewing current knowledge of the subject, the qualitative and quantitative information obtained in field studies of lightning disturbances on electric-power systems has been outlined. Data on frequency of occurrence of thunderstorms, and magnitude and wave shape of voltages and currents produced on systems have been summarized (*pages 483–500*).

New Transformer. In the design of 40,000-kva transformers for a generating station, use of a new steel, "Hipersil", which has a magnetic-saturation value one-third higher than previously used materials, has resulted in appreciable savings in weight and dimensions, making it possible to ship the transformers completely assembled and ready to operate (*Transactions page 916–18*).

Insulation Protection. In an investigation made to determine the impulse-failure voltage of oil-immersed paper insulation samples made from materials used in distribution transformers, volt-time puncture curves were obtained from tests on the wave front that showed the puncture voltage as a function of time for different thicknesses of insulation (*Transactions pages 912–15*).

Metering Progress. Further developments in the art of metering electric energy during the period from 1900 to the present are surveyed in the second part of a report on the history of the art prepared by the AIEE committee on instruments and measurements; parts III and IV will appear in subsequent issues (*pages 469–78*).

Insulation Materials Symposium. Under auspices of the National Research Council's Conference on Electrical Insulation and the American Chemical Society, a symposium on electrical-insulation materials was held September 11, 1941; abstracts of the papers presented appear in this issue (*pages 516–17*).

Styrene as an Insulating Medium. A review of the status of styrene as an insulating material shows that it has many potentialities because of its steadily decreasing cost, its mixing characteristics, its versatility, and its relative inertness to moisture (*pages 478–80*).

Bushing Tests. The results of power-factor tests on high-voltage bushings at test voltages up to or above operating voltage show the desirability of testing at such high voltages; laboratory findings on bushing deterioration are also reported (*Transactions pages 940–2*).

Impulse Strength and Cable Quality. Results of experiment with impregnated-paper-insulated cables show that the maximum stress obtained from impulse tests is a good measure of the uniformity of taping and degree of impregnation of cable insulation (*Transactions pages 929–34*).

Committee Chairmen. Newly appointed chairmen of AIEE general committees for 1941–42 are introduced to the membership through biographical sketches in the "Personal" section (*pages 504–06*); sketches of technical-committee chairmen will appear in the November issue.

Southern District Meeting. Opportunity for a southern winter vacation is provided by the AIEE Southern District meeting to be held in New Orleans, La., December 3–5 1941; proposed inspection trips and other details are described in this issue (*page 502*).

Numerical Solution of Equations. Two approximation methods for solving equations that cannot be solved explicitly for the unknowns are presented and their application to the solution of such equations demonstrated (*pages 480–2*).

Field Investigation of Insulation. The shielding principles that have made possible field testing by the a-c dielectric-loss and power-factor method have been explained in detail and the history and application of the method traced (*Transactions pages 934–9*).

Three-Phase Metering Combinations. Several three-phase combinations of instrument transformers and watt-hour meters have been graded in terms of their relative accuracy under varying conditions (*Transactions pages 925–9*).

Torsional Dampers. The mode of operation of torsional dampers, which have been applied effectively on transmission-line conductors to suppress aeolian vibrations, has been studied and formulas derived for three cases (*Transactions pages 907–11*).

Human-Body Currents. All living tissue has been found to have d-c potential differences between parts with different energy values; a-c potentials in distinct waves are found in tissues related to active motion (*Transactions pages 919–23*).

Coming Soon. Among special articles and technical papers currently in preparation for early publication are: a report of progress in electrical protection by the AIEE committee on protective devices, the first part of which deals with circuit-interrupting devices; an article on special developments in watt-hour meters, the third part of the progress report on metering sponsored by the AIEE committee on instruments and measurements; a report on the performance characteristics of line-type lightning arresters prepared by the lightning-arrester subcommittee of the AIEE committee on protective devices; a paper on transient overspeeding of induction motors by R. W. Ager (A'24); a paper on symmetrical nomenclature of three-phase circuits by Bryce Brady (M'37); a paper describing a cathode-ray oscillograph with rotating-drum camera by E. G. Downie (A'35); a paper on the use of the recovery-voltage analyzer to determine circuit recovery characteristics by G. W. Dunlap (A'35); a paper on sensitive ground protection for transmission lines and distribution feeders by E. T. B. Gross (M'40); a paper describing a device for analyzing the performance of turbine governors by W. O. Osbon (M'41); a paper on the modern a-c network calculator by W. W. Parker (M'37); a paper describing an automatically reclosing breaker for co-ordinating distribution systems by H. L. Rawlins (M'41) and J. H. Wallace (A'41); a paper on criteria for neutral stability of wye-grounded primary, broken-delta secondary, transformer circuits by H. S. Shott (A'40) and H. A. Peterson (M'41); a paper on the communication facilities of the United States Forest Service by A. G. Simson; a paper on the equal-volt-ampere method of designing capacitor motors by P. H. Trickey (M'36); and a paper on high-voltage d-c flashover of solid insulators in compressed nitrogen by J. G. Trump (A'31) and James Andrias (A'41).

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Progress in the Art of
Metering Electric Energy

II—Growth and Development

Progress in the art since 1900 is discussed in this second in a series of four articles on the historical background of the art sponsored by the AIEE committee on instruments and measurements, the first of which appeared in the September issue

DURING THE YEARS from 1900 to the present, the art of metering continued to develop. This period may be divided roughly into two parts: from 1900 to 1925; and from 1925 to the present. During the first part of the century progress was mainly in the direction of improvements in methods; after 1925 the art might be said to have reached its majority, but this does not imply that progress ceased. Meters were adapted to changing sociological requirements, and improvements in accuracy, accessibility, and durability continued to be made.

The factors and forces that helped to create the art of metering electric energy continued to aid its growth during the first quarter of the 20th century. The human element remained as vital as ever. The names of the men who further developed the art are passed over here, not because these men are less important than the pioneers, but because time and space will not permit giving so many their due. In the manufacturing field the one- or two-man engineering departments that were general in 1900 grew to sizable staffs of capable meter engineers, every one of whose contributions is worthy of mention if it were possible. In the operating field all over the United States engineers just as capable contributed equally with the manufacturers to the advancement of the art.

The technological contributions consisted chiefly of improvements in methods, such as, for example, the early steps taken to make meters adaptable to modern quantity production. Important discoveries of new material also had a profound effect upon the art, but there has not been a new fundamental theory of metering since the days of the pioneers. In spite of the tremendous progress made, our engineers today still are striving for smaller and less expensive meters with greater and greater accuracy over wider and wider ranges of load. They still are endeavoring to make the meter even less vulnerable to tampering, even to "tampering" by the weather. Yet paradoxically, they have worked equally hard to make easier the task of those charged with maintaining and calibrating the meter, by increasing the accessibility of its adjustments. Finally, there has been no cessation in the effort to increase the period during which the meter can be "shut up and left alone" without loss in accuracy, until at the present time this period is measured in years instead of months.

Tables I to IV inclusive depict more specifically the trends described. The largest single-phase meter ever offered commercially in the United States was the Shallenberger meter of 1894; by 1900, the size of meters in general had been reduced to about one-fifth and their weight to about one-fourth the volume and weight of Shallenberger's meter. By 1925 the Westinghouse Electric and Manufacturing Company was offering the industry the smallest meter ever manufactured in the United States; namely, the type *OB*.

The principal reason for the large initial reduction in size and weight of the meters offered by all manufacturers was the substitution of magnetic core structures that were nearly closed paths for the wide-open magnetic circuits used in most meters prior to 1900.

Early in the period 1900–25, shapes were changed from rectangular or square to the round patterns that are now universal. Glass covers appeared quite early, but they were generally secured in place by studs that protruded through the glass covers. Wing nuts with washers were used to fasten the covers in place. The so-called studless glass cover did not become universal until the end of this period.

An important addition to the metering art was represented by the meters manufactured by the Fort Wayne Electric Corporation* during the early 1900s. Most interesting of these meters, which are no longer made, were those designed by E. J. King and known as the "*K*" line. The first *K* meter appeared in 1899. This was followed by the *K*1 in 1908 and the *K*2 and *K*3 in 1909. All these

This report was initiated and sponsored by the AIEE committee on instruments and measurements as part of its regular activities for 1940–41, under the following direction: I. F. Kinnard, West Lynn, Mass., chairman; A. S. Albright, Detroit, Mich., vice-chairman; T. S. Gray, Cambridge, Mass., secretary. Personnel of subcommittee on watt-hour meters: A. S. Albright, chairman; D. T. Canfield, Lafayette, Ind., editor-in-chief; A. L. Brownlee, Chicago, Ill.; A. B. Craig, Boston, Mass.; J. S. Cruikshank, Baltimore, Md.; C. L. Dawes, Cambridge, Mass.; A. P. Good; Stanley Green, Lafayette, Ind.; F. C. Holtz, Springfield, Ill.; H. C. Koenig, New York, N. Y.; Paul MacGahan, Newark, N. J.; C. V. Morey, New York, N. Y.; H. C. Rankin, Boston, Mass.; A. R. Rutter, Newark, N. J.; F. B. Silsbee, Washington, D. C.; G. R. Sturtevant, Lynn, Mass.; and H. L. Thomson, Hartford, Conn.

Following publication of part IV in ELECTRICAL ENGINEERING, the whole report will be issued in pamphlet form.

* Founded in 1881 by R. T. McDonald as the Fort Wayne Electric Light Company, for the manufacture and installation of arc lamps, the Fort Wayne company sold a majority of its stock to the Thomson-Houston Electric Company in 1888; was reorganized as the Fort Wayne Electric Corporation in 1894. In 1899 it was purchased by the General Electric Company, which had been formed in 1892 by the consolidation of the Edison General Electric and Thomson-Houston Electric companies and consequently held the latter company's controlling interest in the Fort Wayne company. The name Fort Wayne Electric Corporation was retained until 1911, when it was changed to the Fort Wayne Works of the General Electric Company.

Table I. Westinghouse Electric and Manufacturing Company

Shallenberger

Conrad

Type OA

Type OB

Type OC

Type CA

Type	Year	Volume, Cu. In.	Weight, Lbs.
Shall.	1894	712	41
Conrad	1898	147	12
OA	1910	147	11½
OB	1924	78	5
OC	1932	98	6½
CA	1934	140	7½

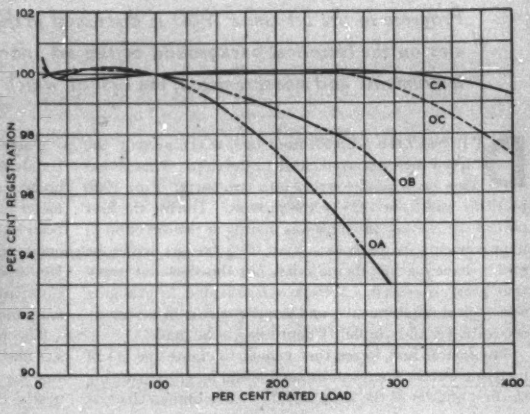
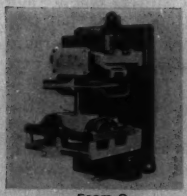


Table II. General Electric Company



Form C

Type I

Type I-14

Type I-16

Type I-20

Type I-30

Type	Year	Volume, Cu. In.	Weight, Lbs.
Form C	1897	401	20
I	1903	178	10
I-10	1909	118	8⅛
I-14	1913	105	8¼
I-16	1927	125	8¼
I-20	1934	140	9
I-30	1940	140	7⅞

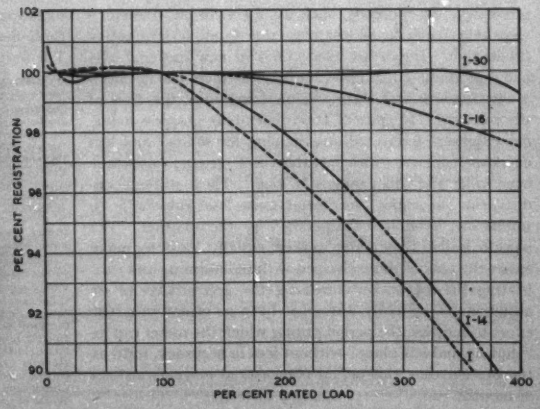
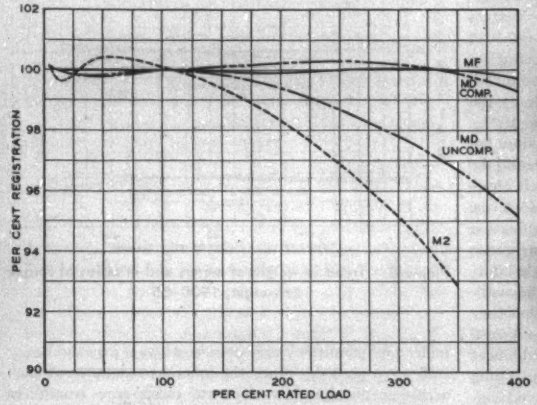


Table III. Duncan Electric Manufacturing Company

Type	Year	Volume, Cu. In.	Weight, Lbs.
Fort Wayne	1896	396	17½
Duncan			
M, M1	1913	183	10½
M2	1915	108	10½
MD	1927	108	10½
MF	1934	140	7⅛
MF	1938	140	7



Ft. Wayne Duncan

Type M & M1

Type M2

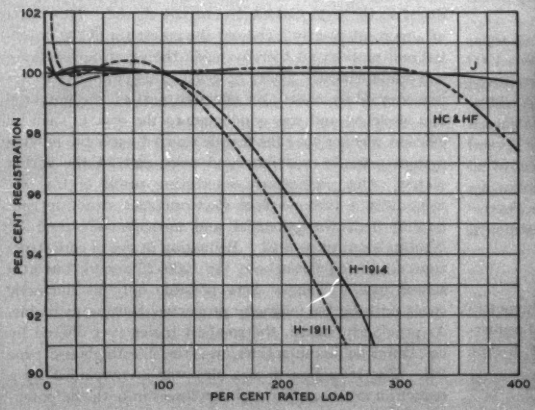
Type MD

Type MF

Type MF

Table IV. Sangamo Electric Company

Type	Year	Volume, Cu. In.	Weight, Lbs.
Gutmann	1899	412	18½
H	1911	115	10½
H	1914	126	11
HC	1927	129	10
HF	1934	140	9
J	1940	140	8



Gutmann

Type H

Type H

Type HC

Type HF

Type J

meters made use of a single cylindrical moving element with the driving element working on the section towards the back of the meter and the braking magnet or magnets acting on the side towards the front of the meter.

Until about 1910 manufacture by both the Duncan Electric Company† and the Sangamo Electric Company was confined to d-c meters, because of the complete domination of the Tesla and Shallenberger patents, held by the Westinghouse company. Upon the expiration of these patents and the resumption of manufacture of a-c meters by those two companies, a sharp break in the cost of meters occurred. The all-time low came in 1915 and 1916 when a-c, five-ampere, two-wire meters were selling for $6.25, each. Following this low there was a gradual increase in price until a high of $9.25, exceeded only by the $15 price for Shallenberger's meter, was reached in 1921.

Test schedules or test periods, the intervals of time between inspections of the meter, theoretically should be determined by the time that the meter may be left alone without its registration changing appreciably. However, the test schedule has long been a subject of specification by the several regulatory commissions, and therefore varies considerably in various states in the Union. Little information on the length of the test interval seems to be available for the first ten years following 1900. Since that time the periodic test period has been gradually increased until at the present time six-year periods are in effect and longer ones are feasible. Although, as seen by the accompanying load curves in tables I to IV, the accuracy improved considerably between 1900 and 1925, the modern flat-load characteristic did not appear until load compensation became universal at the very end of that period. The final phase of this development will be discussed later.

The progress depicted by tables I to IV inclusive is external and nontechnical in character, although its attainment depended on technical improvements in the mechanism of the meter itself. This technical improvement is largely internal and, although important from the standpoint of meter performance, adaptability, and maintenance, it would require for adequate explanation a vast amount of detail and ample illustration. Space is available for only a few of the more important items.

Four different manufacturers were contributing separately to the progress of the art of metering between 1900 and 1925. Whenever a particular item is known to be the exclusive development of a specific company, it will be so stated. In other cases, facts and figures will be chosen indiscriminately from information furnished by the several manufacturers, and should be considered as typical of all manufacturers. For the sake of convenience, the following discussion is grouped under three headings, the electromagnet system, the moving system, and the adjustments, and will be confined to a-c meters.

THE ELECTROMAGNET SYSTEM

The electromagnet systems employed in the early meters were inefficient principally because of the large and numerous air gaps employed. To produce sufficient torque under such conditions large cross-sections of iron and heavy coils were needed. Since the inherent reactance of such arrangements was low, separate closed-core reactances were placed in series with the voltage coils. This was done not alone to limit the current taken by these coils and to minimize frequency errors, but also to introduce sufficient time lag in this current so that shading coil lagging would be able to produce the exact quadrature relation previously stated as essential.

Almost immediately, however, drastic reductions in size and weight were made. These reductions were made possible by two fundamental improvements in the meter's design. First, disks were substituted for cups and cylinders, thereby tremendously reducing the air gaps required; and second, a magnetic, nearly closed shunt path was introduced in the potential electromagnet circuit. This latter arrangement greatly increased the reactance of the potential coil proper and thereby made the separate reactance coil unnecessary. Since, however, this shunt path was not completely closed, an effective part of the potential flux could be and was conducted to the disk in such an efficient manner that the torque exerted upon the moving system actually was increased over that of the earlier meters. One particularly interesting result of this development is the one-piece electromagnet structure containing both the potential and current coils used by Westinghouse since 1910. Reduction in size of core structures continued throughout the 1900–25 period, but at a slower rate. Changes were possible only as magnetic steels with better magnetic properties became available. As previously stated, the smallest meter ever offered by an American manufacturer was the Westinghouse type *OB*. The reduction in size also was accompanied by a reduction in the copper and iron losses in both the poten-

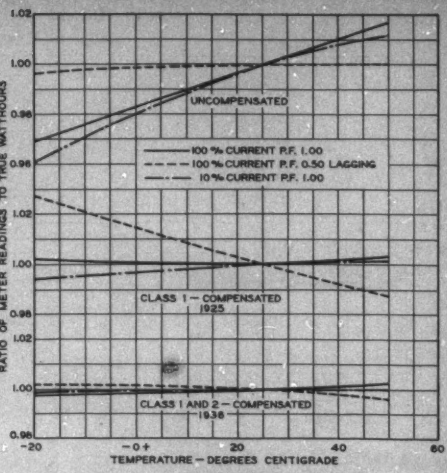


Figure 8. Trend in weight of meters and in ratios of torque to weight, 1900–25

† The Duncan Electric Manufacturing Company was founded originally by Thomas Duncan in 1901 as the Duncan Electric Company (see part I of this report).

tial and current coils. Curve 5 of figure 8 shows this latter improvement very effectively. This particular curve was supplied by the Sangamo company, but is indicative of the general trend.

THE MOVING SYSTEM

For the purpose of this discussion, the moving system consists of the disk, disk shaft, upper and lower bearing, register and retarding magnets. The term "moving element" refers to the disk and shaft only. The retarding magnets never move but they are always associated intimately with the moving element and hence may be considered part of the moving system.

The first improvement in the moving element consisted in the substitution of flat disks for cups or cylinders. The second was the use of one disk to which both the driving and retarding elements were applied.

The third major improvement was the substitution of aluminum for copper as a material for the disk. These advances resulted in a greatly reduced weight of the moving element which, coupled with the increased torque of the more efficient electromagnet system, brought about a tremendous increase in the ratio of torque to weight. It is this ratio as well as the actual torque and weight that constitutes an important criterion of probable meter performance. One early meter had a weight of moving element of 140.0 grams and a torque of 15 milligrams, with a resulting torque-to-weight ratio of approximately 0.1. For many years now a ratio of 3 to 1 or larger has been common practice. The trend in weight and ratio values from 1900 to 1925 is well illustrated by curves 2 and 3 of figure 8.

Early in the 1900s anticreep holes replaced the iron-wire type of anticreep device used on both the commutator and the first induction meters. This resulted in the reduction of the weight of the moving element. As previously stated, the practice of compensating for the exceptionally low inherent friction of the moving system will cause a meter disk to rotate slowly, especially if subjected to mechanical vibrations, until a perfect dynamic balance is attained. Although such drifting will cause negligible registration, it is definitely undesirable. As a remedy, two small holes are placed diametrically opposite in the meter disk. When one of these holes comes under the influence of the potential electromagnet the distortion in the eddy currents induced in the disk acts as a brake. Thus the disk is prevented from revolving more than half a revolution before a load is placed on the meter.

The speed at which the moving element was designed to run at full rated load varied widely. Of the several factors affected by the speed of the moving element, the test constant is the most obvious. One has but to look in the "Metermen's Handbook" at a table of watt-hour-meter constants to note that a wide range of speeds has been used by the several manufacturers and even by the individual manufacturer. If there is any trend, it was upward during the early part of the 1900s and downward since that time. As a typical example, note curve 4 in figure 8.

Bearings for the moving element of a watt-hour meter have presented, since the beginning, one of the problems most difficult to solve satisfactorily. From the first, the bearing developed by the clock art was adopted. The lower bearing which carried the weight of the moving element consisted of some form of steel pivot running in a jewel cup of sapphire. The top bearing, which functions only as a guide bearing, consisted of a polished pin running in a polished brass or bronze ring. The first major change in the bearing was pioneered by the Westinghouse company, which, about 1902, produced a lower bearing consisting of a polished steel ball placed between two sapphire jewel cups. This type of bearing has been used by the company ever since and at the present time has come into general use in American meter practice. Synthetic sapphire jewel bearings were first introduced by the Duncan company about 1915, and have been used by that company ever since. Until very recently, further modification in the bearings has been in the direction of improvement in the mechanical arrangement of the housing and mounting of the pivots, balls, and jewels, and the addition of dirt and dust guards. Finally, noncorrosive metals have been substituted in upper and lower bearings, thereby greatly prolonging the expected life.

Some early registers were of the cyclometer type, but, in general, the United States has favored the pointer form, because such friction as is inevitable is at least constant, and therefore can be compensated for by the light-load adjustment. The number of dials used varied from three or four to eight. In general they were not direct reading, and multipliers were necessary. Quite early in the 1900s four dials became standard practice, as did the direct-reading register. The latter seems to have been introduced first by the Westinghouse company in 1898. In 1938 the industry also recognized the use of five-dial registers as being good practice where it was desired to reduced the number of meters having dial constants other than one.

From the beginning, permanent magnets were used in watt-hours meters for the essential retarding force. Improvements in these magnets up to 1927 consisted mainly in the use of better magnet steels and alloys as they became available and in improved methods of heat treating and aging such magnets.

Frame mounting of the entire moving system appeared first in the General Electric Company's type I meter in 1903. It is common practice in all meters today.

THE ADJUSTMENTS

Watt-hour meters have three adjustments. A full-load adjustment is necessary in order to set the base speed of the meter correctly to that speed at which it is designed to operate. A light-load adjustment point is essential in order to set the friction-compensating device to the place where it just neutralizes the inherent friction of the moving element. Finally there is the so-called lag or inductive-load adjustment which creates the quadrature relation at unity power factor between the potential-coil flux interlinking the disk and the flux generated by the current electromagnet. The earliest meters, in general, had only full-load and inductive-load adjustments. In

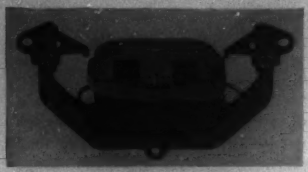


Figure 9. Current core with overload compensator in place

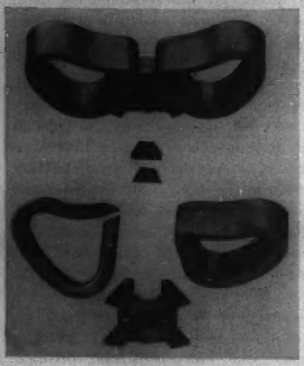


Figure 10. Method of applying class I temperature compensation

the few instances where friction compensation was used, it was not made adjustable.

Two methods of making the full-load adjustment have been used since the very beginning. One of these consists in moving the magnets radially as a unit either in toward the meter shaft or out toward the disk periphery, thereby decreasing or increasing the radius of action of the braking force, which in turn increased or decreased the speed of the disk for a given load. The other commonly used method is to move a magnetic shunt closer to or farther from the poles of the magnets, thereby decreasing or increasing the effective flux that passes through the disk. This in turn increases or decreases the speed of the disk. Both methods have been proved to be perfectly satisfactory and have undergone no basic changes.

The first light-load adjustments were of the magnetic type. The Duncan Fort Wayne meter (illustrated in table III), patented in 1896, shows such a device. It consisted of a steel rod that functioned magnetically to produce a slight auxiliary torque upon the cup armature. The shaded-pole electromagnet type was first introduced by the General Electric Company (form C-1 meter) in 1898. It functions electrically, and consists of a rectangular closed conducting loop around a portion of an electromagnet pole. The assembly was arranged adjustably so as to produce a slight torque upon the disk.

From the first, the lag or inductive-load adjustment has been either a short-circuited plate, similar to the light-load plate, around the potential pole, made adjustable radially or vertically with respect to the disk; or a coil of wire wound around the pole terminating in a pigtail made of resistance wire. The resistance of this coil, and therefore the amount of lagging it will produce, is varied by including more or less of the resistance wire in the coil circuit before it is soldered closed.

There has been no basic change in the nature of these adjustments since their adoption, but great improvements have been made in their accessibility to the meter tester, in the elimination of back lash, and in permanence of the adjustment once made. Such obvious improvements as marking the adjustments to indicate the direction in which to move them to increase the speed of the meter were surprisingly slow in appearing, but are now universal.

IMPROVEMENT IN LONG-RANGE ACCURACY

Prior to 1925 comparatively little attention was paid to certain subordinate characteristics of the watt-hour meter, one of which was its lack of accuracy on overloads. Much had been done to improve the meter performance up to and including full rated load but, as can be seen by the load curves in tables I to IV inclusive, in all meters showed a pronounced falling off in registration of overloads.

Early in the 1920s the basic character of domestic loads began to undergo a change. During this decade the combination of inventive genius, technological advancement, and energetic sales promotion in the field of domestic appliances of all sorts resulted in greatly increased demands upon the domestic electric service. Space heaters, irons, ranges, toasters, and water heaters were developed, perfected, and marketed with such success that the older domestic-service installations became taxed to full capacity if not actually overloaded. Along with this load-building apparatus also developed a host of motor-driven appliances and some devices operating on very low currents, such as, for example, electric clocks, bell-ringing transformers, and certain types of radios. The operators found that if a meter with a rating large enough to measure the heavy loads accurately was installed, it would be insensitive to the light loads; and conversely, a meter with a rating low enough to measure the light loads accurately would fail to measure the heavy loads accurately. To remedy this situation the manufacturers further perfected the watt-hour meter and gave it a performance standard really remarkable in the field of measurements. Thus a modern watt-hour meter of 5-ampere rating will record energy with a high degree of precision from a fraction of an ampere to 20 amperes. Such performance is accomplished by what has become known as overload compensation. All meters since about 1925 are classified broadly as compensated meters. As seen by the load curves in tables I to IV, the so-called "flat-load curve characteristic" was first obtained up to 200 per cent, then 300 per cent, and finally, by 1940, 400 per cent was reached by all manufacturers.

In order to appreciate how such performance is made possible it is necessary first to understand why a meter slows down on overloads. The major reason is that the current flux, which together with the potential flux creates the torque developed by the meter disk, also acts as a retarding force in the same manner as does the permanent magnet flux, although in a lesser degree. Thus a 50 per cent increase in the current flux, which accompanies, for example, a 50 per cent increase in load, will not produce a

50 per cent increase in speed of the disk since the *retarding torque* is also increased. In this respect the driving torque increases with the first power of the current flux but the retarding torque caused by this same flux increases as the square of this flux. Up to nominal load this effect is negligible, since the increase in retarding torque is only a fraction of the total retarding torque, but with overloads this is no longer true and an appreciable inaccuracy would result if this effect were not neutralized in some manner.

Two methods can be used to counteract this tendency both of which are employed today. The first is to decrease the speed at which the meter is designed to operate by increasing the permanent-magnet strength. This increases the ratio between the total retarding torque and that produced by the increase in current flux so that the latter is again a negligible proportion. There is an obvious limitation as to the range of overload to which this principle may be extended.

Another method consists in introducing a magnetic shunt between the poles of the current electromagnet. This shunt becomes saturated and thereby redistributes the current flux on overloads in such a manner that more of it cuts the disk than normally would do so for a given increase in that flux.

O. T. Bláthy, a Hungarian, seems to have been the first to apply magnetic diverters and saturable members for the purpose of improving load curves. Certain patents issued to Bláthy as early as 1900 show devices of this character. Between 1900 and 1927 many American engineers worked on the problem. The Sangamo company was the first company in the United States to apply overload compensation to its watt-hour meters by the shunt or magnetic-diverter method and the General Electric Company was the first to obtain inherent long-range accuracy by decreasing the speed of the meter.

Meters with improved overload recording accuracy were offered by the American manufacturers in several forms. With the type *OB*, *MD*, and *HC* meters, the Westinghouse, Duncan, and Sangamo companies introduced diverters of one form or another. With the type *I*-16 meter General Electric Company lowered the speed. With the type *I*-30 meter General Electric Company added a diverter, and with the type *J* meter the Sangamo company also lowered the speed. With the type *MF*, the Duncan company introduced a diverter (figure 9) designed to saturate progressively. Today the meters manufactured by all the companies mentioned have load curves that indicate excellent performance up to 400 per cent of nominal rating.

TEMPERATURE COMPENSATION

Another inherent characteristic of the watt-hour meter is its change in accuracy with changes in ambient temperature. This phenomenon began to receive considerable attention in the early 1920s. As with the overload problem, it was the operators who provided the impetus behind the investigation. They recognized that meters, whether installed in or out of doors, were subjected to wide variations in ambient temperature. This was particularly true of rotating standards that had to be carried from house to house in all kinds of weather. In short, they discovered seasonal variations in meter registration that could not be explained except as being caused by seasonal changes in ambient temperature.

This led to researches by I. F. Kinnard and H. T. Faus, of the General Electric Company, and others, resulting in discoveries as to how and why a meter's accuracy changes with changes in temperature and also how the meter could be compensated for such changes.

Kinnard discovered that temperature effects on a watt-hour meter are of two classes. In class I he grouped all those effects which produce a change in speed with a change in temperature, but are independent of the power factor of the load being metered. Of the several class I temperature effects, the most important is the weakening of the permanent magnets with increase in temperature. However, this loss in strength is restored when the magnets return to normal temperature. In class II he grouped those effects which produce a change in speed of the meter and also vary in magnitude with the power factor of the load being metered. The most important class II temperature effect is the change in the lagging of the meter with changes in ambient temperature. In other words, the change in temperature causes a shift in the phase

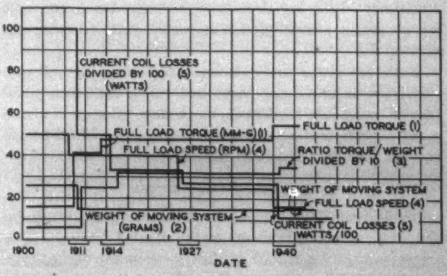


Figure 11. Temperature curves of single-phase meters

position of the potential flux due to the change in the effective resistance of the potential and lag circuits. Since the nature of these two classes was radically different, it was necessary to develop two different methods of compensation. Class I temperature compensation consists in applying to the permanent magnets a magnetic shunt consisting of an alloy of nickel. The permeability of this shunt changes with temperature in such a manner as to correct for the change in the strength of the magnets that would result if no such shunt were applied. More specifically, the permeability of the shunt decreases with an increase in temperature, causing more of the retarding flux to enter the disk. Thus the retarding flux threading the disk is kept constant even though the magnets have temporarily weakened (see figure 10).

The compensation for class II temperature effects must operate upon the lag or inductive load adjustment in such a manner as to effect the changes in lagging resulting from changes in temperature. There are several ways of apply-

ing this compensation but all operate to vary the amount of lagging in such a way as to oppose the change in the lagging caused by changes in temperature.

The General Electric Company in 1925 was the first to apply class I temperature compensation and it has been standard construction on all their meters since that date. Class II temperature compensation was not applied at that time. Figure 10 is an illustration of the method employed. The two trapezoid-shaped shunts illustrated were made of a nickel alloy and placed as shown between the lower poles of the permanent magnets.

Class II temperature compensation was slower in arriving because its application in a simple practical form presented greater electrical and mechanical difficulties. At first manufacturers were content with an attempt to minimize the class II errors without actually compensating for them. In pioneer efforts toward compensation the Duncan company tried bimetallic strips actuating the position of an adjustable lag loop. The General Electric and Sangamo companies perfected compensating means in which the reactance of the lag coil circuit varied with temperature because of the introduction in its magnetic circuit of a small amount of temperature-responsive nickel alloy. The Westinghouse company developed a compensation that was effective because of the change in resistivity of the lag circuits with temperature, one such circuit being placed in the magnetic path carrying the current flux.

Both the latter methods have the advantage of simplicity, with no moving parts, and one or the other is employed on all four modern meters today. Figure 11 shows a set of temperature registration curves which illustrate the advance that has been made.

THE DETACHABLE METER

In the year 1928, the Westinghouse company produced the first detachable meter in the United States. This meter was the forerunner of the now common socket-type meter. The development that ultimately perfected the socket-type meter is one of the outstanding accomplishments in designing to meet new operating requirements.

The socket meter as it is arranged today is illustrated in figure 12*a*. A meter of the standard type is mounted upon a plate with its leads connected to switch-blade lugs on the back of the plate. The switch-blade lugs extending back of the plate are plugged into switch receptacles in the socket. The meter and its plate then are sealed to the socket by a suitable sealing ring. The entire arrangement has the obvious advantage of reducing the work of installation and subsequent change. Moreover, since socket meters may be installed out-of-doors without extra protection, there results the additional advantage of accessibility coupled with economy. It is sometimes inconvenient and occasionally impossible to gain access to meters in interiors at the particular time when such access is desired. This situation is more acute where temporary residences predominate, as, for example, in summer cottages.

The type *CS* meter and the type *S* socket, brought out in 1933, greatly improved the detachable structures. The acceptance of the idea became so widespread that arrangements were made in 1934 to allow all other American manufacturers to use the construction, with the result that an interchangeable mounting for all makes was developed.

The detachable meter is another step forward in the process of making the meter more tamper-proof. Both its construction and its method of installation tend to make tampering more difficult and more easily detected if tried. To attempt to police some 20,000,000 locations would be impossible. The psychological way to overcome this situation is to place the meter out-of-doors in public view, where the public will act as the policing power, thereby lessening the liability to attempts at altering or damage. Various reports have indicated that this psychological deterrent operates to a high degree in the reduction of tampering.

STANDARDIZATION OF THE TYPE A METER

The year 1934 is another important milestone in the progress of the art of metering electric energy. The weight and volume figures in tables I to IV show that in that year all the manufacturers produced meters of substantially identical weight and size. A careful study of the pictures of these meters shows that the exteriors were strikingly similar, and the dimensions of bases, glass covers, and terminal chambers are identical. The standardization also included connection boxes and protector cases, with convenient test facilities all of which conformed to the requirements for both indoor and outdoor installations (see figure 12*b*). In this year it became possible to replace a meter of one manufacture with that of another without changing the wiring, testing facilities, or mounting arrangement. This resulted in much greater flexibility in replacing parts and the like, and enabled operators greatly to reduce their stocks of meters and accessories.

In this year also was introduced the use of aluminum-alloy die-cast bases and frames. Use of this material was also extended to new standardized mountings and housings for "*A*"-type meters. This resulted in improved appearance and greater resistance to weather and corrosion, and greatly reduced likelihood of theft.

ALNICO MAGNETS

In 1936 there was introduced into watt-hour meter construction a new permanent-magnet material called Alnico. Alnico is a trade name given to an alloy developed and made available in the United States by the General Electric Company. Its chief constituents are iron, nickel, aluminum, and cobalt. Unlike older forms of magnets, which were forged to shape from bars, Alnico magnets are cast or sintered to shape and hardened by proper heat treatment. The outstanding property of this material is its very great coercive force for a given weight and volume.

The first application of Alnico in a watt-hour meter was made by the Duncan company in its type *MG* two-element meter in 1936. Such a meter is shown in figure 13. This application was made primarily to take advantage of the reduction in size and weight which the new alloy afforded. In 1938 the same company used Alnico magnets

Figure 12a. Socket-type meter

Figure 12b (right). Type A meter and standardized connection box

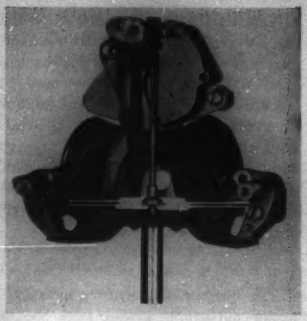


Figure 13. Meter mechanism using Alnico magnets

in a single-phase meter and pointed out the resultant improved resistance to the effect of surges caused by lightning.

About this time the power companies were giving more attention to meter decalibration resulting from lightning surges. Apparently the increase in outdoor and rural installations was subjecting more meters to the influence of current surges caused by lightning, particularly in sections where electrical storms were prevalent. In these sections an occasional meter was found running appreciably fast because of weakened retarding magnets and this was attributed to surges activated by the lightning. As a result of these findings there developed a demand for a meter whose retarding magnets were surge-proof.

As is so often the case, more than one solution of the problem was worked out. First, Alnico magnets were found to be much less affected by external or internal magnetic forces which tend to demagnetize them than are unshielded magnets of other materials. Second, it was discovered that if chrome-steel magnets were surrounded by or covered with a heavy coat of good conducting material, such as copper, this would act as a shield to protect the magnet from the detrimental effects of surges. The Duncan, General Electric, and Sangamo companies have adopted the first solution. The Westinghouse company prefers the second method, and copper-plates the magnets electrolytically with a coating 0.015-inch thick.

THE PRESENT STATUS OF THE QUEST FOR A LIFETIME BEARING

The earliest meter-committee minutes on record discussed the importance of the meter bearings and sought to stimulate specific improvement of the existing forms as far back as 1890. Since that time researches have been carried on continuously by operators and manufacturers seeking a lifetime bearing. By a lifetime bearing is meant one that will last as long as the meter itself, and always function satisfactorily as a bearing.

It is impossible to cover in detail all the work that has been done on meter bearings since 1890. It can be stated, however, that all this work contributed to the solution of the problem and helped to bring the quest for a lifetime bearing to its present status.

The recent application of noncorrosive material to the ball bearing introduced by the Westinghouse company in 1902 is considered today by many authorities as one solution of the lifetime bearing problem. Further confirmation and other possible solutions resulted from the more recent work of F. C. Holtz of the Sangamo Electric Company, Stanley Green of the Duncan Electric Manufacturing Company, and I. F. Kinnard and J. H. Goss of General Electric Company.

Holtz made a study of the actual behavior of a bearing by plotting the path on the jewel over which the pivot or ball traveled under various conditions of load on the meter, including voltage coil excitation only. So peculiar were the patterns he found that he has titled the study "The Anomalous Behavior of Meter Bearings." This classic study gives evidence that the ball bearing is superior to the steel pivot.

Green's contribution to the solution of the problem was the development of a new pivot material called "Nobeloy." Nobeloy is an alloy of gold, silver, platinum, copper, and zinc which promises to add great staying quality to bearings on which it is used.

A third and important step toward the present status of the lifetime bearing was the development and application by Kinnard and Goss of cobalt-tungsten alloy as a material for balls and pivots. With this corrosion-resistant material, the products of wear are much less abrasive than with other materials. [1]

As far as the jewels are concerned, the sapphire is still the accepted material. There has been a general change to artificial sapphires in place of natural stones, but the sapphire is still universally used. In this connection orientation of the jewel has been found to give superior performance. By orientation is meant the cutting of the jewel with respect to the internal structure in such a manner as to give it maximum possible resistance to wear and shock.

The bearing situation as it exists today may be summed up by a statement of what each of the manufacturers recommends as the nearest approach to a lifetime bearing. The Westinghouse company used the carbon-steel ball exclusively for many years but more recently has adopted the chrome-steel ball. The General Electric Company uses the cobalt-tungsten ball or pivot as desired. The Duncan company furnishes the Nobeloy pivot or the chrome-steel ball as requested. The Sangamo company offers the cobalt-tungsten ball or pivot according to customer preference.

SUMMARY

The quarter of a century between 1900 and 1925 saw major reductions in the size, weight, and cost of the American-made watt-hour meter. Possibly of still greater importance was the increased accuracy of performance in spite of these reductions. Moreover, the increased "staying power" or ability of the meter to maintain this accuracy over longer periods of time without adjustment was of tremendous importance.

A tendency towards standardization is in evidence during this period. Individuality became more and more replaced by common sizes, shapes, and construction details. Adjustments became more similar and much simpler of operation. By the end of the period metermen familiar with one meter did not need to spend as much time and effort to become equally familiar with another make as they had at the beginning.

Many of the improvements if studied individually would be considered uninteresting details. Yet none of them was insignificant, for taken collectively they constitute a major advance. The increase in maintenance of meter accuracy over wider ranges and longer periods of time, the reduction in first cost, and the lowering of maintenance cost were largely due to these apparently minor details.

Since 1925 progress has continued in directions previously considered, and other developments made which are important in the growth of the art.

Load and temperature compensation not only gives higher registration precision from the smallest loads to 400 per cent overload, but at the same time permits meters of a given rating to be used for a wide range of loads and variations in ambient temperature.

The detachable meter reduces the work of installation and provides greater accessibility for reading the meter. Since the same sockets can be used for different manufacturers' meters, the stocks that utilities need keep on hand have been reduced greatly. In addition, the possibility of tampering has been minimized.

In meters of the bottom-connected type, standardization of the terminal arrangements, improved design of the bases and covers, and standardization of mountings and housings and test facilities also have resulted in greater flexibility, accessibility, ease of testing, and reduction in the possibility of tampering.

The introduction of Alnico magnets for watt-hour meters has resulted not only in lighter, more compact meters, but also has the advantage of making the meter more resistant to the detrimental effect of surges from lightning or other sources. For the latter purpose, shielding the older form of magnet with copper also has been found effective.

Since 1925, the quest for a lifetime bearing has received even more consideration than in previous periods. Basic researches and life tests on bearings have resulted in two new bearing materials, Nobeloy and cobalt-tungsten alloy, and have substantiated previous belief in the merits of the ball bearing.

Styrene and Its Insulation Potentialities

T. R. SCOTT

In the development of new insulating materials, those which have large-scale application in other fields will prove most economical. Styrene, one such material, has decreased steadily in cost.

IN 1937 the writer reviewed in some detail the history of polystyrene as an insulating material from 1913 onwards.[1] The intervening four years have shown a marked increase in the use of styrene in the electrical field, as well as decided progress in technical control and application. In view of these achievements, it seems desirable once again to review the general situation.

The question is sometimes asked, "Why concentrate on polystyrene?" There are undoubtedly other polymeric materials of undisputed merit, among them polythene and polyisobutylene. One can only point out that high-grade characteristics alone are not sufficient to cause commercial development and interest. Economics must be considered.

It is apparently a law in the insulation field that low cost can be obtained only by the utilization of materials that also have applications on a considerable scale in other fields. If oils, petrolatums, paper, rubber, textile fabrics were useful to mankind only for insulation purposes, the

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cost of these materials would be many times greater than it is at present and the urge to develop cheaper methods of production would be many times less. The insulation engineer, therefore, in his search for newer and better types of insulants continually must bear in mind the fact that the material he selects for special investigation and progressive development preferably should have widespread applications in other fields, so that, the demand being great, production can be on a large scale and cost consequently can be reduced to a low value.

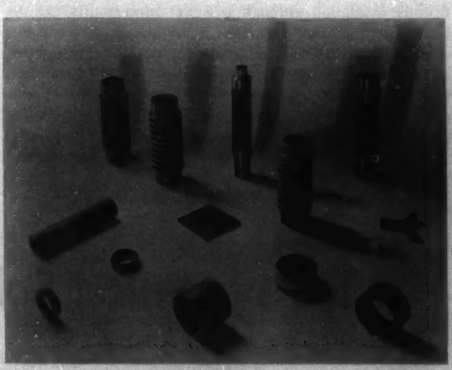
Styrene is such a material and recent years have seen a steady decrease in its cost. There are indications that this decrease in cost will continue for some time so that, other things being equal, that is, present-day price standards being unaffected by war-time economic upheavals, the cost eventually may drop as low as 20 cents per pound. Under such price conditions the blends or compounds of styrene with paper, rubber, and other materials, which have proved to be such excellent insulants, will become serious competitors of many insulants which at present appear to be firmly established on the basis of "sufficient quality" for low price. As a result, general improvement in the level of insulation quality may be achieved.

This question of combination of synthetics with other well-known or new insulating materials to form new types of insulation raises another point in connection with the selection of synthetics for intensive development work. A greater field of application is likely to be obtained for a synthetic which has good "mixing" characteristics compared with one which is "inert" in this respect. The combinations of styrene with rubber and paper have already been dealt with by the writer. Through these combinations it is often possible to insert a third material in order further to modify or cheapen the insulation. A simple illustration was encountered in the days when a remedy was being sought for the seepage of oil into styrene joints while these joints were being constructed and polymerized.[2] Oils and monostyrenes are compatible in practically all proportions, but, during polymerization, all but a small percentage of the oil is thrown out to give a heterogeneous mixture of oil and polystyrene. Introduction of quantities of chlorinated aromatic hydrocarbons, however, formed a common bond and improved conditions. In other words, the plasticization of polystyrene by a material such as arochlor permitted the introduction of oil as a third member of the compound.

It is noteworthy that while this action can be carried out with normal polystyrene, it is also possible so to treat polystyrene that it is not compatible with chlorinated aromatic hydrocarbons to any appreciable degree. In other words, styrene can be adjusted either to make use of this characteristic or not, according to the design plans of the insulation engineer. This versatility of styrene is another characteristic which recommends it to the engineer.

The problems associated with the direct plasticization of polystyrene are still mainly in the stage of laboratory experiment and patent investigation. It is claimed by some that styrene cannot be plasticized by any material having a zero electric moment. It can be argued, therefore, that all plasticizers degrade the electrical characteristic of polystyrene. This may be the case (the writer does not admit it yet); nevertheless, a variety of useful plasticized polystyrene compounds can be produced, are being produced, and more will be produced. It must be remembered that all electrical insulation is a compromise between mechanical and electrical characteristics. The finest dielectric is useless unless it can be manipulated and applied in a form giving the desired mechanical characteristics for each specific practical application in which it is to be employed. With a dielectric power factor of 0.03 per cent available from pure polystyrene, it is generally of little practical importance if this power factor is degraded to 0.06 per cent in order to build up suitable mechanical characteristics for the intended application.

Furthermore, electrical insulating value should not be judged entirely upon basic laboratory values derived from tests taken on the material in a standardized condition. Other attributes may play an important part in the commercial value of the material as an insulant. The resistance of organic materials to the passage of moisture is a pertinent illustration. (A good discussion of this characteristic of organic materials is given by Taylor, Herrmann, and Kemp.[3])



Various articles made from bonded styrenated paper. The two plain bushings in the background have been fitted with copper end caps ready for attaching to a cable end

Fibrous insulation is used extensively in the electrical industry. Such insulation requires drying and, thereafter, protection from reabsorption of moisture. Full protection apparently cannot be afforded by any organic material, but organic materials, each according to its intrinsic characteristic, can slow down the rate of reabsorption to a rate which is commercially acceptable. Fibrous insulation in general cannot be rated as having an infinite life but rather as having a finite life of sufficient length for commercial purposes, providing it is suitably protected. In combinations of fibrous and synthetic materials the important factor may be not so much the basic insulation

value of the fibrous and synthetic materials, respectively, but the aging effect indicated under humidity of the combination of materials in the insulation.

The important factor in determining this characteristic is more likely to be the moisture-transference characteristic of the synthetic than its basic insulation value. This transference constant may be appreciably improved by plasticization (for example, cellulose acetate[3]). If so, the degradation of the original insulation value of the basic synthetic material may be more than compensated for by the improved over-all result. In the case of polystyrene, the moisture pickup is comparatively low and, therefore, the change of electrical characteristics with humidification is slight. Polystyrene, however, has a transference constant of the order of that of polyvinyl chloride, which, although low, is nevertheless appreciable. Plasticization may degrade the basic power factor of polystyrene but it may also reduce this transference constant and thereby produce a better over-all result.

This particular problem of moisture reabsorption by fibrous insulation through organic impregnants can be attacked in another way, that is, by the reduction of the affinity of the fiber for moisture, for example, by esterification (including acetylation) of the fiber.[4,5] Esterification is, however, a somewhat costly procedure, and it is desirable on the score of economics to keep the degree of esterification as low as possible consistent with economic gain caused by increased life. The more resistant the organic impregnant to moisture transference, the less the degree of esterification necessary for any desired duration of life of the insulation. Plasticization of synthetics such as polystyrene therefore may be extremely advantageous regardless of basic electrical values.

It has been shown that polystyrene is a material of immense potentialities in the insulation field, in view of its price ranking, its mixing characteristics, its versatility, its relative inertness to moisture, and other qualities. It may be anticipated that as engineers become more familiar with styrene, through utilization of the forms of insulation that already have been developed, they will find new uses for it. In this they will be aided by the continuous development work now proceeding on the modification of both mechanical and electrical characteristics, particularly by admixture with one or more better-known insulating materials.

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The Numerical Solution of Equations

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ASSOCIATE AIEE

A helpful tool not very generally known among engineers is the use of approximation methods for the solution of equations which cannot be solved algebraically; the author describes and illustrates two such methods.

IN engineering work many of the equations or systems of equations that are encountered may be solved explicitly for the unknowns. Some of these solutions are well known, such as the formula for the roots of a quadratic equation in one unknown and the use of determinants in solving a system of linear equations in any number of unknowns. If it is very difficult or impossible to solve explicitly for the unknowns of a system of equations, some approximation method may be used.

The first and perhaps best known of these approximation methods is the graphical method,[1] which is easily understood but may be quite tedious and inaccurate, especially if more than one unknown is present. Horner's method is well known and is used to approximate the real roots of algebraic equations. Two other approximation methods are Newton's method[1,2] and the iteration process.[1] Although Newton's method is really an iteration process, the two will be considered separately in this article, the purpose of which is to explain the use of these two methods and to illustrate by means of typical engineering examples their application to the numerical solution of equations.

The solution of an equation in one variable by Newton's method is carried out as follows: Suppose that $f(x)$ is the function whose root is to be found, and that this function is graphed as the curve $y=f(x)$ in figure 1. Choose a value of x, such as a; then the length $\overline{PA}=f(a)$. The line $\overline{PB}$ is drawn tangent to the curve $y=f(x)$ at P, and the slope of this tangent is $f'(a)$, where $f'(x)$ is the derivative of $f(x)$ with respect to x. The length $\overline{AB}$ is then equal to $-f(a)/f'(a)=h$, and the number h is called the first correction, since $(a+h)$ will usually be closer to the root at

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C than a was. This process should be repeated until the root is obtained as accurately as needed. Example 1 in the appendix illustrates the method. If it should happen that the method does not converge toward the root of $f(x)$, a value a closer to the root should be tried.

Newton's method may be applied to a set of equations with any number of unknowns, although it is perhaps most useful in solving an equation of one unknown. For the case of three equations with three unknowns, that is, $f_1(x_1, x_2, x_3)$, $f_2(x_1, x_2, x_3)$, and $f_3(x_1, x_2, x_3)$ it is required to find the values x_1, x_2, and x_3 which will make all three functions vanish simultaneously. Choose $x_1=a_1$, $x_2=a_2$, and $x_3=a_3$ such that for these values f_1, f_2, and f_3 are small, and calculate also the nine partial derivatives of these functions. The first corrections are then:

$$h_1 = -\frac{1}{D}\begin{vmatrix} f_1 & \frac{\partial f_1}{\partial x_2} & \frac{\partial f_1}{\partial x_3} \\ f_2 & \frac{\partial f_2}{\partial x_2} & \frac{\partial f_2}{\partial x_3} \\ f_3 & \frac{\partial f_3}{\partial x_2} & \frac{\partial f_3}{\partial x_3} \end{vmatrix} \qquad h_2 = -\frac{1}{D}\begin{vmatrix} \frac{\partial f_1}{\partial x_1} & f_1 & \frac{\partial f_1}{\partial x_3} \\ \frac{\partial f_2}{\partial x_1} & f_2 & \frac{\partial f_2}{\partial x_3} \\ \frac{\partial f_3}{\partial x_1} & f_3 & \frac{\partial f_3}{\partial x_3} \end{vmatrix}$$

$$h_3 = -\frac{1}{D}\begin{vmatrix} \frac{\partial f_1}{\partial x_1} & \frac{\partial f_1}{\partial x_2} & f_1 \\ \frac{\partial f_2}{\partial x_1} & \frac{\partial f_2}{\partial x_2} & f_2 \\ \frac{\partial f_3}{\partial x_1} & \frac{\partial f_3}{\partial x_2} & f_3 \end{vmatrix} \qquad \text{where } D = \begin{vmatrix} \frac{\partial f_1}{\partial x_1} & \frac{\partial f_1}{\partial x_2} & \frac{\partial f_1}{\partial x_3} \\ \frac{\partial f_2}{\partial x_1} & \frac{\partial f_2}{\partial x_2} & \frac{\partial f_2}{\partial x_3} \\ \frac{\partial f_3}{\partial x_1} & \frac{\partial f_3}{\partial x_2} & \frac{\partial f_3}{\partial x_3} \end{vmatrix}$$

The quantities $x_1=a_1+h_1$, $x_2=a_2+h_2$, $x_3=a_3+h_3$ will be closer to the required solution than the original a_1, a_2, a_3. Again this process should be repeated until the solution is obtained to the required accuracy. Example 2 of the appendix shows a system of two equations with two unknowns that was solved in this way.

In general the closer to the root that the first a or a's are taken, the fewer the number of the repetitions of the process that are needed. Also when near the root, the derivatives do not change very much, and it is often possible to use the same value of the derivative for a number of the repetitions and thus save time.

The method of iteration for one unknown is as follows. Let $f(x)=0$ be the equation whose root is to be found, and separate $f(x)$ into two parts such that $g_1(x)-g_2(x)\equiv f(x)$. Graph the two functions $y=g_1(x)$ and $y=g_2(x)$ as shown in figure 2. Choose $x=b_1$, and solve the equation $g_2(x)=g_1(b_1)$ for x where $y=g_1(x)$ is the curve of lesser slope. The solution of this equation is called b_2 and is closer to the root $x=b$ of $f(x)$. The equation $g_2(x)=g_1(b_2)$ is solved for $x=b_3$, and the process is repeated. The resulting sequence b_1, b_2, b_3, . . . should converge to the desired root. If the curve of greater slope had been used, the resulting sequence would not have converged toward the root. Example 3 of the appendix illustrates the application of this method to a practical problem.

For three equations with three unknowns the iteration method may be applied in a slightly different way. Again let $f_1(x_1, x_2, x_3)$, $f_2(x_1, x_2, x_3)$, and $f_3(x_1, x_2, x_3)$ be the three equations, and assume $x_1=b_1$ and $x_1=c_1$. Substitute these values in f_1 and solve for x_2 to obtain $x_2=d_1$. Substitute $x_2=c_1$ and $x_3=d_1$ in f_2 and solve for x_1 to obtain $x_1=b_2$. Repeat by putting $x_2=d_1$ and $x_1=b_2$ into f_3 and obtain $x_3=c_2$. The sequence b_1, b_2, . . . will converge to the required value of x_1, while the sequences c_1, c_2, . . . and d_1, d_2, . . . will converge to the values of x_2 and x_3 respectively. Example 4 shows the application of this method to four equations of four unknowns. In this example Newton's method in one variable was used also. The equations in this example were arranged so that f_1 which has only two unknowns was used first. This is an advantage, since only one unknown must be assumed, while if f_2 had been used first, two unknowns would have had to be assumed.

Approximate values for the unknowns may be found oftentimes from the physical process from which the equations are derived or from an approximate solution of the equations. The assumed value of μ in example 4, for instance, was taken from an approximate solution. In any of these methods, the closer the first assumed values are to the roots, the less time the method will require for a given accuracy. Sometimes the assumed values are so far away from the required roots that the processes may not converge to a root or may converge to a root other than the wanted one. As an illustration of this last point, example 3 has another root at S_r equal approximately to 102. In actual use, Newton's method, by virtue of its speed, appears preferable for an equation of one unknown. For more than one unknown the method of iteration seems better, since there are no derivatives to be calculated. The final criterion, however, must be the time required to solve the set of equations at hand.

Appendix

Example 1: See reference 3.

$$\log_e \frac{(100)}{(50)} = \frac{1}{0.30}\log_e \frac{0.21(1-x_2)}{x_2(0.79)} + \log_e \frac{1-x_2}{0.79}$$

Put

$$f(x_2) = \frac{1}{0.30}\log_e \frac{0.21(1-x_2)}{x_2(0.79)} + \log_e \frac{1-x_2}{0.79} - \log_e \frac{100}{50}$$

$$f'(x_2) = -\frac{1}{1-x_2}\left(\frac{1}{0.30x_2}+1\right)$$

Choose

$x_2=0.15$
$f(x_2)=+0.7142$ and $f'(x_2)=-27.337$
$h=-\dfrac{f(x_2)}{f'(x_2)}=\equiv-\dfrac{+0.7142}{-27.337}=+0.0262$ first correction
$x_2=0.15+0.0262=+0.1762$
$f(x_2)=0.0712$ and $f'(x_2)=-24.174$
$h=+0.002949$
$x_2=0.1762+0.0029=0.1791$
$f(x_2)=-0.0017$ and $f'(x_2)=-23.86$
$h=-0.0000712$
$x_2=0.1791-0.0001=0.1790$

Example 2: See page 393 of reference 4. Q_1 and Q_2 are the flows in each loop.

$$f_1(Q_1, Q_2) = 1.95\times10^{-3}(200-Q_1)^{1.85} - 1.30\times10^{-3}(Q_1-Q_2)^{1.85} - 0.65\times10^{-3}Q_1^{1.85}$$

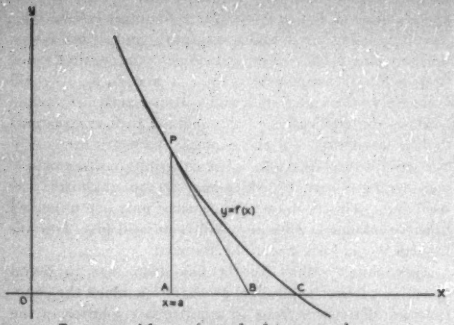

Figure 1. Newton's method in one unknown

$$f_2(Q_1, Q_2) = 0.65\times10^{-3}(200-Q_2)^{1.88} - 1.95\times10^{-3}Q_2^{1.88} + 1.30\times10^{-3}(Q_1-Q_2)^{1.88}$$

Values of Q_1 and Q_2 are sought that will make both f_1 and f_2 zero. Choose

$Q_1 = 110,\ Q_2 = 70$

$f_1 = 2.914,\ f_2 = 1.419$

$$D = \begin{vmatrix} -0.2863+0.0553 \\ +0.0553-0.2627 \end{vmatrix} = 0.0721$$

$$h_1 = -\frac{1}{0.0721}\begin{vmatrix} 2.914 & 0.0553 \\ 1.419 & -0.2627 \end{vmatrix} = 11.68$$

$$h_2 = -\frac{1}{0.0721}\begin{vmatrix} -0.2863 & 2.914 \\ 0.0553 & 1.419 \end{vmatrix} = 7.86$$

$Q_1 = 110+11.68 = 121.7;\ Q_2 = 70+7.9 = 77.9$

$f_1 = 0.163,\ f_2 = -0.018$

$h_1 = 0.599,\ h_2 = 0.064$

$Q_1 = 121.7+0.6 = 122.3,\ Q_2 = 77.9+0.1 = 78.0$

Example 3: See reference 5.

$$-0.1962 \sinh(0.01824S_r) = \sin(0.0555S_r)$$

Put

$$g_1(S_r) = -0.1962 \sinh(0.01824S_r)$$

and

$$g_2(S_r) = \sin(0.0555S_r)$$

Choose

$S_r = 50$

$g_1 = -0.2047$

$g_2 = \sin(0.0555S_r) = -0.2047$

$S_r = 60.3$

$g_1 = -0.2620$

$g_2 = \sin(0.0555S_r) = -0.2620$

$S_r = 61.4$

$g_1 = -0.2685$

$g_2 = \sin(0.0555S_r) = -0.2685$

$S_r = 61.5$

Example 4: The following problem was encountered in rectifier circuit theory. The four unknowns are α, β, μ, ρ.

$$f_1(\alpha,\beta,\mu,\rho) = 2\sin\alpha+2-2\sin\mu-5\cos\mu-5(\cos\mu)\epsilon^{-0.4(\alpha-\mu)}$$

$$f_2(\alpha,\beta,\mu,\rho) = 5\cos\beta+0.479\cos(\beta-1.279)+[2\sin\alpha+2-2\sin\mu-5\times\cos\mu-0.479\cos(\alpha-1.279)]\epsilon^{-0.3(\beta-\alpha)}$$

$$f_3(\alpha,\beta,\mu,\rho) = \frac{5}{3}\cos\beta+\frac{2}{3}\sin\beta+\frac{10}{3}\cos\mu+\frac{4}{3}\sin\mu-2\sin\rho+\frac{2}{3}+5(\cos\beta)\epsilon^{-0.4(\rho-\beta+3\pi)}$$

$$f_4(\alpha,\beta,\mu,\rho) = 5\cos\mu+0.981\cos(\mu-1.373)-\left[\frac{5}{3}\cos\beta+\frac{2}{3}\sin\beta+\frac{10}{3}\cos\mu+\frac{4}{3}\sin\mu-2\sin\rho+\frac{2}{3}+0.981\cos(\rho-1.373)\right]\epsilon^{-0.3(\rho-\rho)}$$

Values of α, β, μ, and ρ are required such that f_1, f_2, f_3, and f_4 are all zero.

Assume

$\mu = -75°$ or -1.309 radians

$f_1 = 2\sin\alpha+2.638-1.294\exp[-0.4(\alpha+1.309)]$

This equation may be solved for α by using Newton's method in one variable, and the result is $\alpha = -50°37'$. The values of $\mu = -75°$ and $\alpha = -50°37'$ are substituted in f_2.

$$f_2 = 5\cos\beta+0.479\cos(\beta-1.279)+1.359\exp[-0.3(\beta+0.883)]$$

From this $\beta = 101°43'$; the three values of μ, α, and β are then substituted in f_3, and f_3 is solved for ρ to obtain $\rho = -179°7'$. The three values $\alpha = -50°37'$, $\beta = 101°43'$, and $\rho = -179°7'$ are substituted into f_4, and f_4 is solved for μ. This new value of μ is $-77°9'$, and this value of μ is used in f_1 to obtain $\alpha = -65°10'$. The process is repeated to obtain:

$\beta = 101°32'$

$\rho = -176°8'$

$\mu = -77°10'$

$\alpha = -65°23'$

$\beta = 101°32'$

$\rho = -176°9'$

The last four values were taken as the final values.

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4. Hydraulic Analysis of Water Distribution Systems by Means of an Electric Network Analyzer, T. R. Camp and H. L. Hazen. *Journal* of the New England Water Works Association, volume 48, 1934, pages 383–407.

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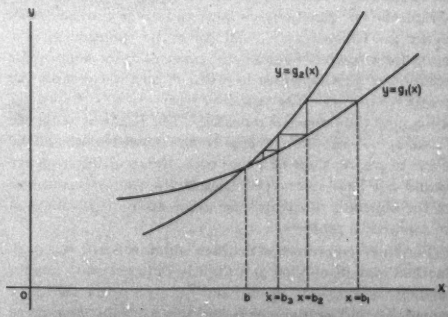

Figure 2. The iteration method in one unknown

Lightning Phenomena

III—Field Studies

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FELLOW AIEE

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In this concluding article in a series of three, field studies of lightning disturbances on electric-power systems, made with the aid of instruments described in part II (September issue), are reviewed. (Part I, in the August issue, reviewed the general characteristics of lightning phenomena.) The qualitative and quantitative information obtained in these studies has enabled remedial measures to be devised and the lightning performance of systems improved, thereby reducing the system outages from this cause.

FROM the standpoint of the lightning performance of electrical systems the frequency of occurrence, as well as the magnitude and wave shape of the voltages and currents produced on systems, is important.

FREQUENCY OF THUNDERSTORMS

W. H. Alexander[45] has published isoceraunic charts, figures 24 and 25, showing the frequency of occurrence of thunderstorms throughout the United States. Figure 24 shows the total number of storm days (days on which thunder could be heard) to be expected each year in different parts of the country, and figure 25 the total number of storm days recorded each month over a 30-year period. To determine the average number of storm days occurring in any month the figures on the monthly charts should be divided by 30. The data for these charts were obtained for the period from 1904 to 1933 by the United States Weather Bureau.

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45. For all numbered references see list at end of article.

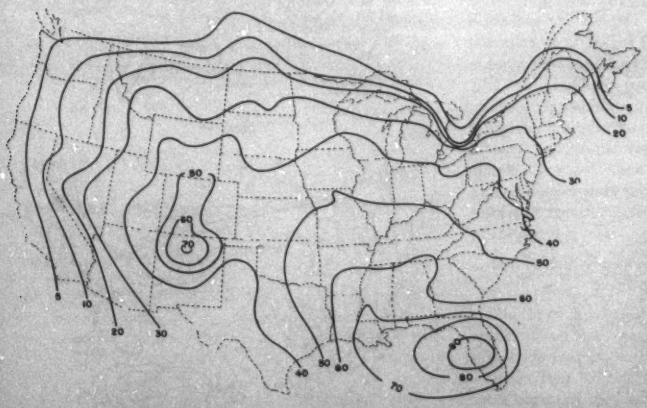
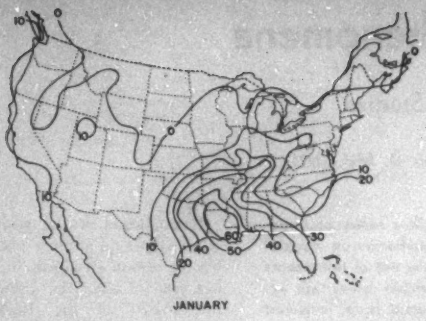


Figure 24. Annual isoceraunic map showing the number of thunderstorm days per year, Alexander[45].

Examination of the yearly chart shows an average number of about 30 storm days per year for all of the United States east of the Rocky Mountains. There are two pronounced centers of activity. The greatest is in Florida, more than 90 storm days. The other is in New Mexico with a maximum of about 70 storm days. The number of storms in the Pacific Coast area is considerably lower, averaging from 3 to 10.

The month of least storms in the United States is January, with the center of thunderstorm activity over Louisiana and with some activity in the Gulf and South Atlantic States. For each succeeding month the storm activity increases throughout the country, spreading rapidly in the southeastern states and reaching a peak for most of the country in July, when the number of storms per month for all but the Pacific Coast area has reached an average of about 9 storm days with a maximum of about 22 in South Florida and New Mexico. By August the number of storm days has started to decrease everywhere but on the Pacific Coast and in September it is rapidly decreasing. In the Pacific Coast region the activity is more nearly constant, but has a slight peak in September.

Although these charts do not give an indication of the intensity, duration, extent, or number of storms occurring, they constitute the best data available. Also, a comparison of the data obtained by several investigations on the seasonal variation of the number of lightning disturbances produced on power systems in a given region with the number of storm days indicates fairly close agreement. That is, the relative number of system disturbances recorded per month varies with the months in practically the same manner as the number of storm days per month. An example of this is shown on figure 26 for data on distribution-arrester discharge currents.[46]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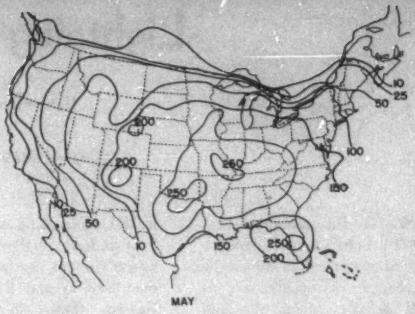
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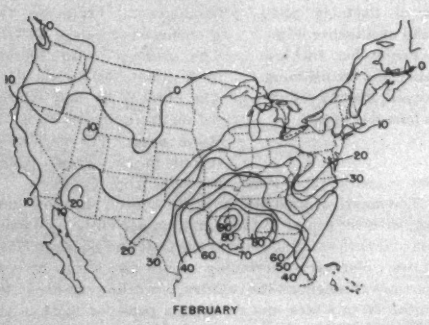
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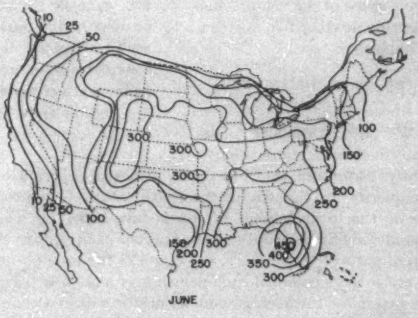
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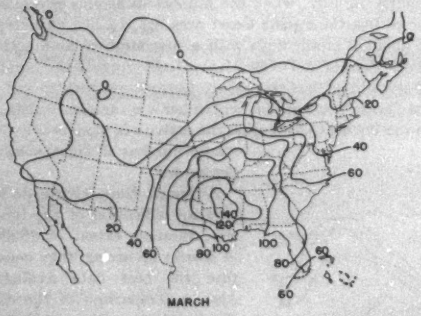
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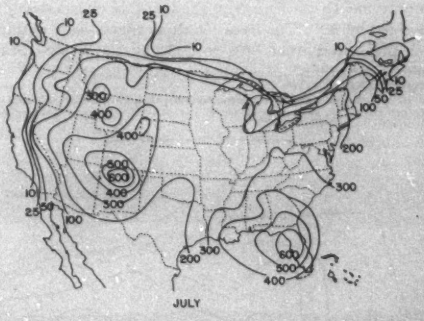
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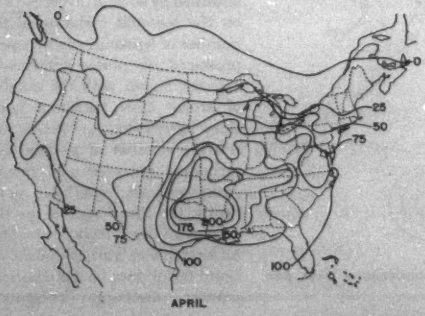
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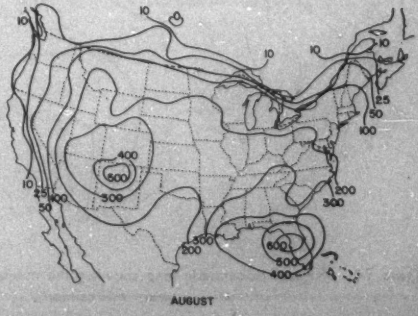
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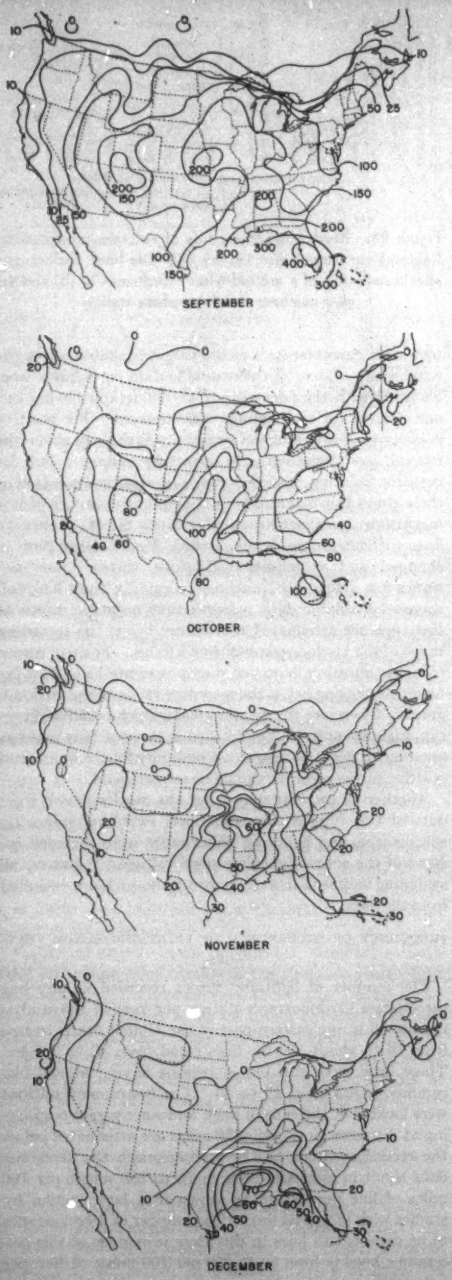


Figure 25. Monthly isoceraunic maps showing the total number of thunderstorm days occurring each month over the 30-year period from 1904 to 1933, Alexander.[45] To determine average numbers of storms per month divide numbers on maps by 30

However, the number of such disturbances varies widely from year to year and for systems in different regions, even though the isoceraunic levels of the regions are nearly the same. There are several reasons for this. The number of surges reaching arresters, transformers, and the like, of course, should depend to a great extent upon their density of installation and on the degree of shielding of the lines.

There are also other important reasons. Both local topographical and meteorological conditions appear to cause large localized variations in storm densities. In mountainous regions thunderstorms are generally of the heat or mountain type. Their formation depends on local meteorological and topographical conditions. Thunderstorms of the cold-front and warm-front types depend for their formation on the interaction of adjacent cold and warm air masses, which frequently cover hundreds of square miles. Their formation thus does not depend wholly on local topographical conditions. However, storms of this type, which are common to the East and Middle West, appear to follow more or less defined paths that do depend upon topographical conditions. Storms of this type sometimes follow rivers and valleys.

For such reasons the number of lightning disturbances on any one system depends upon its location relative to local topographical conditions and prevailing storm paths. Thus, it is rather difficult to establish from data obtained on a limited number of systems mean figures for the number of electrical disturbances to be expected. The best available method seems to be to base such data on the isoceraunic levels and to give as many data as possible on the range of variance that these localized conditions might introduce. The isoceraunic level of 30 storms per year is commonly used for this basis. When considering data regarding the number of strokes to transmission lines or the number of surges produced on transmission lines, one is interested in the number per unit length per unit time. The common basis used here is the number per hundred miles of transmission line per year. However, for considering the lightning performance of such equipment as arresters and transformers, the number of disturbances should be based upon the number occurring per unit of apparatus per unit time. In this discussion, surges in arresters or transformers are based on the number per single-phase unit per year.

SURGE-VOLTAGE MEASUREMENTS ON TRANSMISSION LINES WITH THE KLYDONOGRAPH

The first important field studies of surge voltages on transmission lines were begun in 1925[47] with 26 three-terminal klydonographs installed on 27 systems varying in voltage from 6.6 to 220 kv. Subsequently, other studies were begun in the United States.[48–53] Investigations also have been made in South Africa and Japan.[53] At the time these studies were started it was thought that induced

voltages resulting from strokes in the vicinity of a transmission line were the primary cause of system flashover.

In figures 27 to 30 are shown percentage distribution curves of the magnitude of lightning surges obtained from these studies. These curves give data on voltages that might be expected at a given point on a line caused by surges originating at different points along the line. The voltage is, of course, a function of the insulation level and

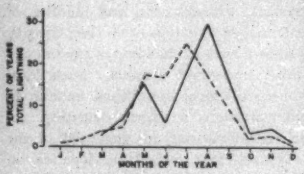


Figure 26. Comparison between variance of disturbances on systems (solid curve) and monthly isoceraunic levels; McEachron and McMorris[46]

the wave shape of the surge. The maximum voltage that has been recorded was 5,000,000 volts and was obtained by Pittman and Torok[54] with a cathode-ray oscillograph from a direct stroke to a conductor of a 110-kv wood-pole line without ground wires. Examination of figures 27*a–d* shows that the voltage decreases with the voltage rating of the line. This probably results primarily from the reduction of insulation strength with reduction of operating voltage. The klydonograph studies indicated that most surges on lines were unidirectional and of positive polarity.

More recent information relating to the currents in lightning strokes indicates that about 90 per cent of all strokes to ground lower negative charge to earth. Such negative strokes produce negative voltages on a transmission line if they strike the line directly but induce positive surges if they strike in the vicinity of the line. In spite of the predominance of the recorded positive voltages, it does not follow that the surges produced on the line at the point of origin are predominantly positive. The recording characteristics of the klydonograph and the at-

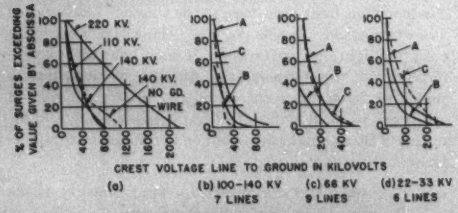


Figure 27. Klydonograph records of voltages produced by lightning[47–52] on transmission lines of various voltage ratings, both with and without ground wires

Curves *A* apply to total lightning surges on lines without ground wires

Curves *B* apply to surges not producing outages on lines without ground wires

Curves C apply to total lightning surges on lines with ground wires

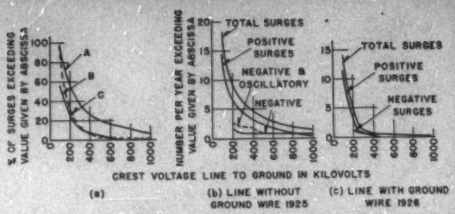

% OF SURGES EXCEEDING VALUE GIVEN BY ABSCISSA
NUMBER PER YEAR EXCEEDING VALUE GIVEN BY ABSCISSA
TOTAL SURGES
POSITIVE SURGES
NEGATIVE & OSCILLATORY
NEGATIVE
CREST VOLTAGE LINE TO GROUND IN KILOVOLTS
(a)
(b) LINE WITHOUT GROUND WIRE 1925
(c) LINE WITH GROUND WIRE 1926

Figure 28. Klydonograph records of voltages produced by lightning on a particular 120-kv 148-mile line[47] before and after installation of a ground wire. Ordinates in (b) and (c) give numbers at a three-phase station

tenuation characteristics of the surges probably affect the conclusions. Most of the available data on polarity were obtained with the normal-type klydonograph having but one element for each voltage measurement. For positive polarity the lower range of sensitivity is slightly above the normal crest line-to-ground operating voltage. But for negative polarity the lower range of sensitivity is two or three times this magnitude. Thus negative surges of low magnitude were not recorded. Most direct strokes to lines without ground wires produce flashover resulting in chopped and sometimes oscillatory waves. Short-tail waves are attenuated much more rapidly than long-tail waves. Available data indicate that negative waves of this type are attenuated to voltages below the recording range of the klydonograph in 4 or 5 miles. Positive surges of longer duration, however, may propagate 15 or 20 miles before decreasing below the recording range of the klydonograph. Therefore the distance from which positive surges can originate and still be recorded is three or four times as great as for negative surges. Consequently the number of positive surges recorded should be proportional.

Another factor that may color the results drawn from data of this type is that sometimes switching surges resulting from the lightning disturbance were recorded instead of the actual lightning surge voltage. However, all switching surges that were known to be such are excluded from the data.

FREQUENCY OF OCCURRENCE OF LIGHTNING SURGE VOLTAGES

The number of lightning surges recorded at any one three-phase klydonograph station per year in the studies conducted in the eastern part of the United States varied from 15 to about 100 for lines rated from 33 to 220 kv. These lines were situated in regions having annual isoceraunic levels from 25 to 40. The instrument stations were located at the ends of lines, and since surges originating at distances in excess of 20 miles are attenuated below the recording range of the klydonograph the foregoing data result in estimates of from 75 to 500 surges per 100 miles of line per year. As shown in a later section by studies with magnetic links,[55] the number of direct strokes to be expected to lines in this class in regions of this isoceraunic level is from 50 to 250 per 100 miles of line per

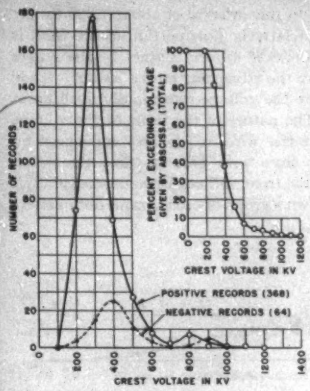
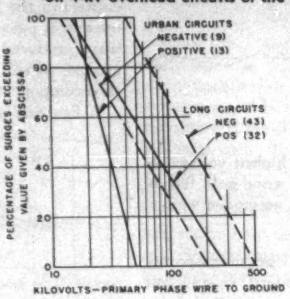
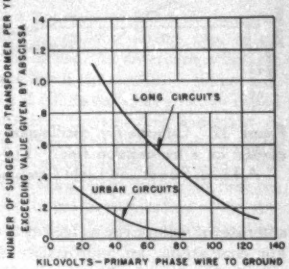

NUMBER OF RECORDS
CREST VOLTAGE IN KV
POSITIVE RECORDS (368)
NEGATIVE RECORDS (64)
PERCENT EXCEEDING VOLTAGE GIVEN BY ABSCISSA. (TOTAL)
CREST VOLTAGE IN KV

Figure 29 (left). Amplitude and frequency of surge voltages measured by Rokkaku on the Inawashiro lines in Japan[53]

Figure 30. Lightning surge voltages recorded by Halperin and McEachron[57] on 4-kv overhead circuits of the Commonwealth Edison Company




LONG CIRCUITS
URBAN CIRCUITS
NUMBER OF SURGES PER TRANSFORMER PER YEAR EXCEEDING VALUE GIVEN BY ABSCISSA
KILOVOLTS—PRIMARY PHASE WIRE TO GROUND

year, with an average of about 100. Thus the klydonograph data indicate that approximately half of the significant surges are produced by direct strokes. Since those strokes that induce voltages are about equal to those that strike the line, and since the line attracts strokes only from within a narrow band adjacent to it, then those indirect strokes that produce surges must strike the ground close to the line. This has been verified[56] by a stroke observed to have struck ground 200 feet from a transmission line of the Public Service Company of New Jersey and 1,600 feet from a lightning recording station on the line. No surge voltage was recorded in this case, although klydonographs and a cathode-ray oscillograph were in operation at the time to record voltages on the phase wires.

In general, induced voltages, since they seldom exceed 500 kv, rarely produce outages on 66-kv or higher-voltage lines. As the operating voltage of the line decreases the insulation also decreases and induced voltages may produce outages.

In figure 29 are shown data obtained in Japan[53] on a 154-kv line. Because of the lower limit of sensitivity of the instruments and the variance of this with polarity, it is likely that the data below the first peaks for both polarities are questionable.

Figure 30 shows curves of voltages obtained on both rural and urban 4-kv circuits of the Commonwealth Edison Company.[57] These curves indicate that voltages over about 200 kv seldom occur on urban circuits which are much better shielded than the rural circuits where the upper limit of voltages appears to be about 500 kv. Curves also are plotted in this figure showing the probability of surge voltages of different magnitudes reaching transformers.

SURGE-VOLTAGE MEASUREMENTS ON TRANSMISSION LINES WITH THE CATHODE-RAY OSCILLOGRAPH

Studies with the cathode-ray oscillograph of voltages produced on transmission lines were begun in 1928. The relatively few oscillograph stations that could be established did not permit of obtaining many records. In addition, interpretation of the records was difficult because of the influence of such unknown factors as propagation, distortion, and reflection. However, some valuable qualitative and quantitative information has been obtained from these studies. Some of the more important oscillograms are shown in figures 31 to 37.

In figure 31 are seven oscillograms obtained in the Westinghouse studies.[58] All were obtained on steel-pole lines, most of which had ground wires, and the surges originated at appreciable distances from the recording equipment. They indicate fronts of from two to seven microseconds

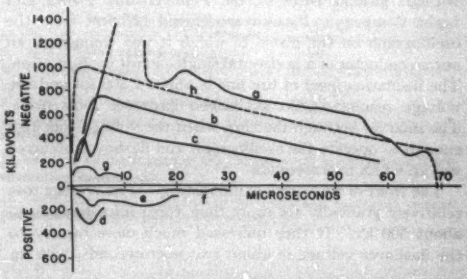


Figure 31. Typical lightning surges recorded with cathode-ray oscillographs[58]

Surge No.	Polarity	Rate of Rise, Kv Per μsec	Crest Kv	Time: To Crest, μsec	Time: To ½ Max. Voltage μsec	Where Taken
a	Neg.	143	Unknown, 1,000 recorded	7 μsec to 1,000 kv		N. J.
b	Neg.	183	750	5	33	Tenn.
c	Neg.	270	550	6	26	N. J.
d	Pos.	137	325	3	4	N. J.
e	Pos.	30	180	5	15	W. Va.
f	Pos.		45		30	N. J.
g	Neg.	167	160	2.5	8	W. Va.
h	Pos.	500	1,000	2	43	Trafford Test

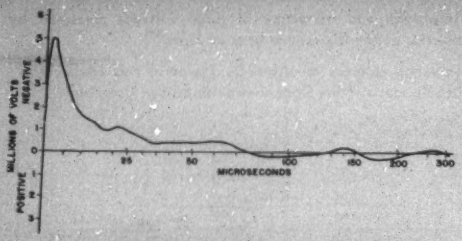


Figure 32. Cathode-ray oscillogram of highest voltage recorded on a transmission line;[54] 110-kv wood-pole line of Arkansas Power and Light Company; no ground wire

and rates of voltage rise as high as 270 kv per microsecond. For comparison, an approximate standard $1^1/_2 \times 40$ test wave is also plotted. The surges of larger magnitude have tails conforming closely to that of the standard wave.

The surge of highest voltage recorded on a transmission line is shown in figure 32. It occurred on a 110-kv wood-pole line without ground wires of the Arkansas Power and Light Company.[54] The oscillograph was located about four miles from the point where the line was struck, and flashover occurred. This voltage wave has a maximum rate of rise of 4,000 kv per microsecond.

In figure 33 is shown the only oscillogram obtained from a direct stroke close enough to the recording equipment that the wave shape before flashover occurred is not distorted by propagation. This oscillogram was obtained by Bell and Price[59] on a section of a 220-kv steel-tower line without ground wires of the Pennsylvania Power and Light Company. Flashover occurred 125 feet from the oscillograph on the phase to which it was connected, an outer conductor of a horizontal single-circuit configuration. The insulation level of the line is about 1,300 kv and the voltage reached 2,800 kv before flashover took place. The interval between the time when the voltage was high enough to operate the oscillograph and flashover occurred was about six microseconds.

The front of this surge is interesting. The voltage rose relatively gradually for more than three microseconds to about 500 kv. It then increased much more rapidly to the flashover voltage in about two microseconds, with an average rate of rise in this interval of about 1,300 kv per microsecond. The relatively slow portion of the front is probably voltage produced before contact of the stroke to the phase wire by the advancing stroke leader. Upon contact of the stroke the voltage rose rapidly until flashover took place. The nature of the front of the voltage wave produced on phase wires is probably influenced by ground wires. For lines with ground wires the initial slow component of the front will not be so marked.

In figure 34 is shown a group of oscillograms obtained by

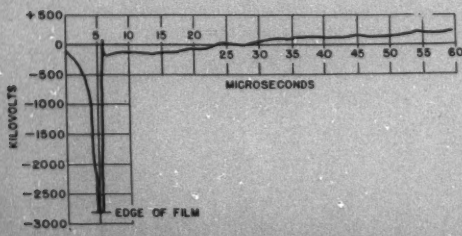


Figure 33. Oscillogram of lightning surge voltage measured at point of origin[59]

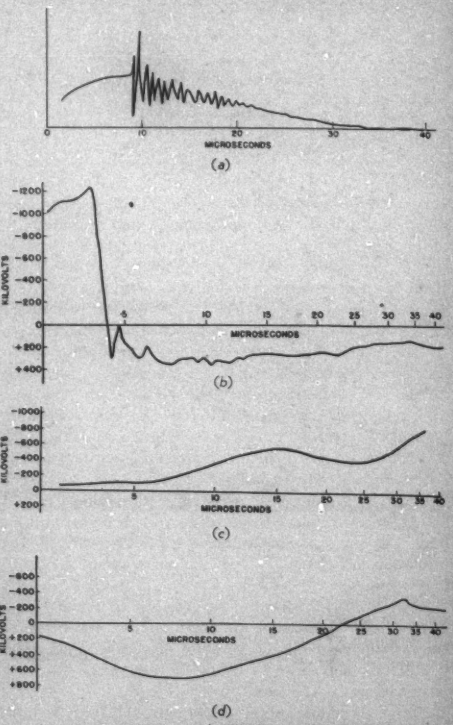


Figure 34. Group of cathode-ray oscillograms of line voltage taken on the Wallenpaupack line[60]

(a). First cathode-ray oscillogram of a lightning surge on a transmission line. The oscillations were caused by flashover on an adjacent phase

(b). Dead-end protective gaps flashed over on all three phases, causing a sharp change in voltage from 1,260 kv negative to 310 kv positive in one microsecond. Flashover took place on front of wave

(c). Record obtained while line was not energized. Voltage was still rising at the end of 36 microseconds and was then suddenly reduced to zero. Subsequent examination of the line indicated a flashover 23 miles away, which appeared to correlate with this oscillogram

(d). The slightly oscillatory nature of this oscillogram is typical of a large group of waves. A cloud-to-ground stroke, at least ten miles distant from the laboratory and some distance from the line, was seen at the instant this record was obtained

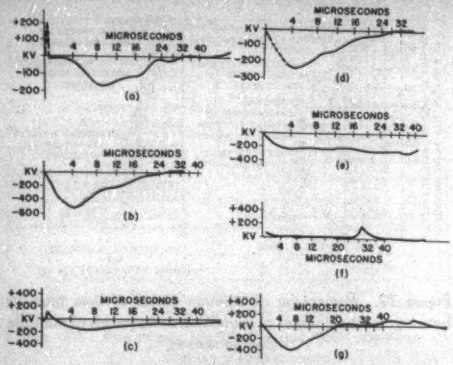


Figure 35. Group of cathode-ray oscillograms of lightning voltage on transmission lines obtained by George and Eaton[62]

the General Electric Company.[60] Figure 34*a* is of interest because it is the first cathode-ray oscillogram obtained of a natural-lightning transient. Figures 34*b–d* are typical of the three groups into which the 16 oscillograms exceeding 300 kv recorded by Smeloff and Price[61] may be classified. Figure 34*b* is typical of records in which flashover occurs close to the recording equipment; figure 34*d* of voltages too low to cause flashover, but which are distorted by both propagation and negative reflections. The reversal of voltage is caused by such reflections; and the sloping off of the front results from propagation and reflections.

Figure 35 shows a group of oscillograms published by George and Eaton.[62] They all are of relatively low voltage and of surges originating quite a distance from the oscillograph station.

An interesting oscillogram which shows the effect of reflections is given in figure 36. This record[58] is of the voltage on a phase wire induced by a stroke to another phase wire three miles from the oscillograph station. The wave front increased at a rate of 143 kv per microsecond to a magnitude considerably beyond the oscillograph range. At approximately 12 microseconds flashover occurred to the adjacent conductor reducing the voltage on the conductor to which the oscillograph was connected. The recorded voltage rose to 1,000 kv after which it decayed to 600 kv in 55 microseconds. At this time the negative reflected wave arrived from the far end of the line, a distance of eight miles from the oscillograph, where it had flashed over a noninductive resistance, thereby modifying the original tail of the wave as shown. This illustrates the typical effect of reflection on the tail of the wave.

These cathode-ray oscillograph studies led to the conclusion that the original voltage produced by the lightning stroke does not persist longer than 200 microseconds, but that successive reflections from different parts of the system may spread the disturbance out to as much as several thousand microseconds. Figure 37 shows oscillograms illustrating this effect obtained by Bell and Price.[58]

The long-duration low-current components of lightning surges, later found to be present, were not recorded. However, they are not important from the standpoint of voltage insulation.

CURRENT MEASUREMENTS

While the voltage on a transmission line is fundamental in determining whether an insulator string, gap, or arrester flashes over, it is difficult to determine what the voltages would be on the line if the insulation did not fail. However, currents are not influenced to as great an extent by flashovers. In addition, currents are important in their bearing on the mechanical stresses and thermal effects set up in protective devices and other equipment. For this reason most of the investigations during the past ten years have been devoted to the determination of the current characteristics of lightning strokes. These investigations can be given three classifications:

(*a*) *Strokes to Open Ground and Tall Buildings.* These comprised the following investigations:

1. Schonland, Malan, Hodges, and Collens[15–17] in South Africa who studied the mechanism of lightning with the Boys camera and by measurement with the cathode-ray oscillograph of the electric field produced by strokes.

2. Stekolnikov and Valeev[22] in Russia who measured, with the cathode-ray oscillograph and high-speed rotating klydonograph, currents in strokes to captive balloons flown to altitudes between 500 and 800 meters and voltages induced by strokes to ground in a short horizontal antenna.

3. McEachron[11,54] who measured currents in strokes to the Empire State Building in New York, N. Y., with the cathode-ray and crater-lamp oscillographs and the surge-crest ammeter.

4. Norinder[24] in Sweden who measured with the cathode-ray oscillograph the magnetic fields produced by lightning strokes.

5. Wagner, McCann, and Beck[26] who measured with the fulchronograph, magnetic surge-front recorder, surge-crest ammeter, and magnetic surge integrator, the currents in tall objects of different heights.

(*b*) *Strokes to Transmission Lines.* These include the following investigations made with the surge-crest ammeter:

6. Lewis and Foust[28] who measured surge currents in transmission line towers, ground wires, counterpoises, and tower masts.

7. Waldorf[34] who measured surge currents in tower legs.

8. Bell[57,58] who measured currents in tower legs and cross braces and in counterpoises.

9. Grunewald[29] in Germany who measured currents in towers.

10. Rokkaku and Katoh[35,70] in Japan who measured currents in tower legs and ground wires.

In addition to the foregoing are the following investigations made with other instruments:

11. McEachron[71] who measured with the crater-lamp oscillograph currents discharged by protector tubes on transmission lines.

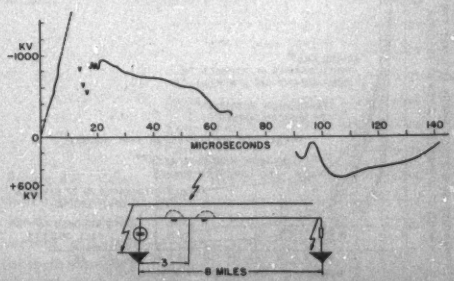


Figure 36. Cathode-ray oscillogram of voltage due to natural lightning showing effect of propagation and reflections[58]

12. Berger[73] in Switzerland who, besides measuring transmission-line tower-leg currents with the surge-crest ammeter, recorded their maximum rate of rise with klydonographs inductively coupled with the tower legs.

(*c*) *Arrester Discharge Currents.* The following investigations were made with surge-crest ammeters:

13. McEachron and McMorris[74] who measured discharge currents in distribution arresters on 120- to 20,000-volt systems.

14. Gross and McMorris[75] who measured discharge currents in station-type arresters on 11- to 132-kv systems.

15. Gruneswald[76] in Germany who measured arrester currents on systems from 6 to 100 kv.

In addition to the foregoing are the following investigations made with other instruments:

16. Collins[68] who used paper-gap recorders to measure discharge currents in arresters on a 24-kv system.

17. Wagner, McCann, and Beck[65] who measured the discharge currents in arresters by means of the fulchronograph, magnetic surge-front recorder, magnetic-surge integrator, and surge-crest ammeter.

MULTIPLE CHARACTER OF STROKES

In figures 38 to 40 are plotted curves giving statistical data on the number of components, the time intervals between them, and the total duration of strokes. These curves represent data on strokes of three general types: (1) strokes to power systems as given by the protector-tube and arrester data; (2) strokes to open country as given by the photographic records and the data on induced voltages; (3) strokes to tall objects. With regard to number of components and total duration, there is a fair check between the curves of each type, but there are important differences between the types. More components and longer durations are recorded for strokes to tall objects. This is probably because tall projections from the earth affect stroke mechanism and cause strokes to them to differ in character from those to ground or to lower objects. Tall objects should influence a greater region of the thundercloud and thus tap more charge centers, causing strokes to have more components and longer durations. Of practical importance is the indication that the records to power systems have fewer components and shorter durations. This results probably from the diminution of the surge current by the following causes: (1) All of the direct-stroke current is not likely to pass through a protective device because more than one may operate, thus dividing the current, or flashovers may occur on the lines thereby limiting the discharge current; (2) the protective device may be operated by attenuated surges from strokes to the system at remote points; (3) the protective device may be discharged by induced surges. Thus some of the smaller components of current may have been reduced to such an extent that they are below the recording range of the instruments, or have voltages associated with them below the operating voltage of the protective device. Arresters and other terminal equipment are therefore exposed to less severe duty than is indicated by the results from direct strokes or strokes to open country. Only about a third of power-system surges are multiple and the maximum number of components recorded is 8. From one-half to two-thirds of the strokes to open country are multiple and as many as 40 components have been photographed.[30]

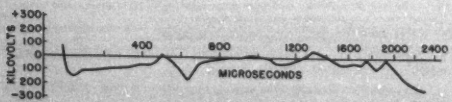


Figure 37. Cathode-ray oscillogram of voltage due to natural lightning which shows the prolongation of the disturbance as a result of successive reflections[59]

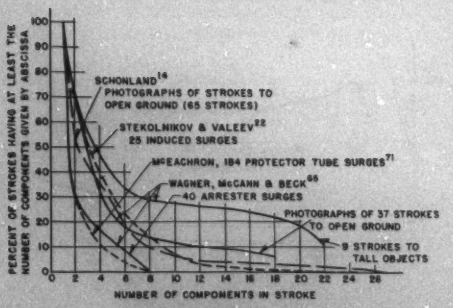

PERCENT OF STROKES HAVING AT LEAST THE NUMBER OF COMPONENTS GIVEN BY ABSCISSA
SCHONLAND[16] PHOTOGRAPHS OF STROKES TO OPEN GROUND (65 STROKES)
STEKOLNIKOV & VALEEV[82] 25 INDUCED SURGES
McEACHRON, 184 PROTECTOR TUBE SURGES[71]
WAGNER, McCANN & BECK[65] 40 ARRESTER SURGES
PHOTOGRAPHS OF 37 STROKES TO OPEN GROUND
9 STROKES TO TALL OBJECTS
NUMBER OF COMPONENTS IN STROKE

Figure 38. Percentage distribution curves of the number of components in lightning strokes

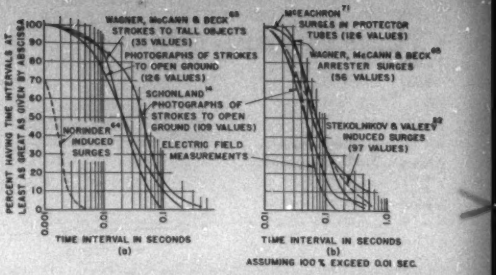

PERCENT HAVING TIME INTERVALS AT LEAST AS GREAT AS GIVEN BY ABSCISSA
WAGNER, McCANN & BECK[65] STROKES TO TALL OBJECTS (35 VALUES)
PHOTOGRAPHS OF STROKES TO OPEN GROUND (126 VALUES)
SCHONLAND[16] PHOTOGRAPHS OF STROKES TO OPEN GROUND (109 VALUES)
NORINDER[64] INDUCED SURGES
ELECTRIC FIELD MEASUREMENTS
TIME INTERVAL IN SECONDS
(a)
McEACHRON[71] SURGES IN PROTECTOR TUBES (126 VALUES)
WAGNER, McCANN & BECK[65] ARRESTER SURGES (56 VALUES)
STEKOLNIKOV & VALEEV[82] INDUCED SURGES (97 VALUES)
TIME INTERVAL IN SECONDS
(b)
ASSUMING 100 % EXCEED 0.01 SEC.

Figure 39. Percentage distribution curves of time intervals between the beginnings of successive components of multiple lightning strokes

Figure 39 indicates time intervals as high as 0.5 second between components. In figure 39*b* the basis of 100 per cent was taken at a time interval of 0.01 second as the resolving power of some of the measuring instruments did not extend below this time. Only about a sixth of the intervals are less than one-half cycle of 60-cycle frequency.

CREST MAGNITUDE OF CURRENTS

Extensive studies have been made both in the United States and abroad with surge-crest ammeter links on transmission lines and in ground leads of lightning arresters. Most of the measurements on transmission lines have been of currents in the legs of towers, although they have also been made of currents in ground wires, phase wires, counterpoise wires, and masts mounted on top of towers.

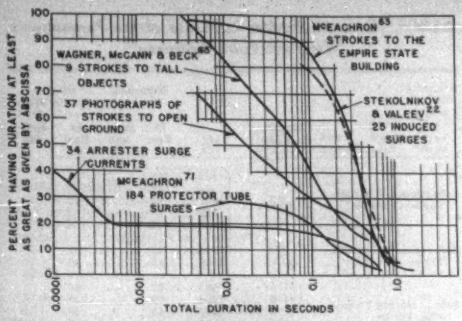

PERCENT HAVING DURATION AT LEAST AS GREAT AS GIVEN BY ABSCISSA
TOTAL DURATION IN SECONDS
WAGNER, McCANN & BECK 65 9 STROKES TO TALL OBJECTS
37 PHOTOGRAPHS OF STROKES TO OPEN GROUND
34 ARRESTER SURGE CURRENTS
McEACHRON 71 184 PROTECTOR TUBE SURGES
McEACHRON 65 STROKES TO THE EMPIRE STATE BUILDING
STEKOLNIKOV & VALEEV 22 25 INDUCED SURGES

Figure 40. Percentage distribution of total duration of lightning strokes

Transmission-Line-Tower Currents. The curves of figure 41, showing the magnitude of currents in transmission-line towers, were compiled only from the currents in the tower thought to be close to the terminating point of the stroke or the tower carrying the most current. The character of the curves is influenced by the minimum current that could be measured by the sensitivity of the links and the minimum current different investigators thought it advisable to include in their data. These minimum values affect both the point regarded as 100 per cent on the ordinate and also the shape of the curve. The minimum tower currents included in the data of Waldorf[55] were about 2,400 amperes and for Bell[68] and Grunewald[69] about 5,000 amperes. The curves of Lewis and Foust[66] comprise some of the data of Waldorf and Bell plus data obtained on other lines in the United States. However, 5.000 amperes was the minimum considered by them.

Before drawing any conclusions from these curves it is well to consider their probable accuracy. The majority of the magnetic-link measurements of steel-tower currents were made on only one leg of the tower, the total current being assumed to be this measurement multiplied by the number of tower legs. Records obtained with links on all tower legs indicate that frequently currents are not equally distributed. Data obtained by Waldorf, shown in figure 42 indicate the mean deviation of an individual tower leg from the mean of the four supporting legs. This deviation appears to decrease as the sum of the four tower-leg currents increases, being about ten per cent above 40,000 amperes. Factors that might cause such discrepancies, are dissymmetry in the counterpoise or other type of grounding or in the tower itself. These factors might even result in differences in wave shape of the component currents. In addition, there are the possible errors of the recording equipment, particularly at low currents. It is probable, however, that some of these effects are minimized by the quantity of data making up the statistical averaging of several hundred records.

Data obtained by Bell[67] who also measured the currents in the tower cross braces show that appreciable current flows in them. His results indicate that a correction factor varying from 1.64 to 2.75, with a mean of about 2, should be applied to the tower-leg current readings for his records. Lewis and Foust[66] say that from 30 to 100 per cent of the main leg currents flowed in the cross braces.

Rokkaku[70] and Schahfer and Knutz[75] made studies in which they measured the main leg currents and the difference between the ground-wire currents on each side of the tower. Assuming this difference to be the total tower current gives an indication of the discrepancy between the total tower current and the sum of the leg currents. Their results are summarized in figure 43, which indicates that this correction factor should increase with the magnitude of the tower current. The curves of figure 41, so far as the authors are aware, do not take this correction factor into consideration and are plotted simply as the sum of the four tower-leg currents.

Direct-Stroke Currents. Figure 44 gives per cent distribution curves for direct strokes as a function of the crest magnitude. Curves 1 to 3, which are for strokes to transmission lines, were obtained by adding the tower-leg currents in all the towers thought to be involved in the stroke. Errors introduced by this procedure are the fol-

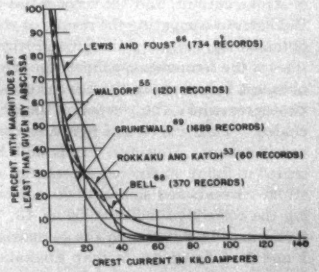

PERCENT WITH MAGNITUDES AT LEAST THAT GIVEN BY ABSCISSA
CREST CURRENT IN KILOAMPERES
LEWIS AND FOUST 66 (734 RECORDS)
WALDORF 55 (1201 RECORDS)
GRUNEWALD 69 (1689 RECORDS)
ROKKAKU AND KATOH 53 (60 RECORDS)
BELL 68 (370 RECORDS)

Figure 41. Percentage distribution curves of tower currents for strokes to transmission lines

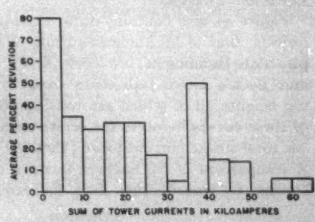


Figure 42. Deviation from equal division of lightning current in tower legs, as obtained by Waldorf[55] from 209 records

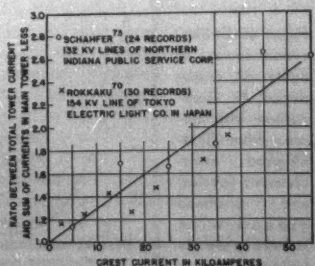

RATIO BETWEEN TOTAL TOWER CURRENT AND SUM OF CURRENTS IN MAIN TOWER LEGS
CREST CURRENT IN KILOAMPERES
SCHAHFER 75 (24 RECORDS) 132 KV LINES OF NORTHERN INDIANA PUBLIC SERVICE CORP.
ROKKAKU 70 (30 RECORDS) 154 KV LINE OF TOKYO ELECTRIC LIGHT CO. IN JAPAN

Figure 43. Relation between total tower lightning current and sum of main tower-leg currents in transmission-line steel towers

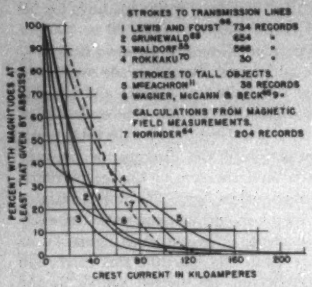

STROKES TO TRANSMISSION LINES
1 LEWIS AND FOUST[66] 734 RECORDS
2 GRUNEWALD[69] 624 "
3 WALDORF[55] 588 "
4 ROKKAKU[70] 30 "
STROKES TO TALL OBJECTS.
5 MCEACHRON[11] 38 RECORDS
6 WAGNER, McCANN & BECK[65] 9+
CALCULATIONS FROM MAGNETIC FIELD MEASUREMENTS.
7 NORINDER[42] 204 RECORDS
PERCENT WITH MAGNITUDES AT LEAST AS GIVEN BY ABSCISSA
CREST CURRENT IN KILOAMPERES

Figure 44. Percentage distribution curves of lightning - stroke currents

lowing: First, the sum of the tower-leg currents may be less than the total tower current; second, the effects of more than one stroke might be involved in summing the currents of different towers; and, third, because of distortion as the result of reflection from other towers, the sum of the crest currents at the towers will not equal the stroke current. The first item tends to indicate a low value of stroke current, and the second and third a high value. Rokkaku in comparing the results of stroke measurements obtained by summing the ground-wire currents on both sides of the terminating point of the stroke with the results obtained by summing the tower currents found that the two agree where the correction factor of figure 43 is included. Their curve 4 of figure 44 takes this factor into consideration. However, Lewis and Foust in data presented in figure 45 showed substantial agreement between stroke currents and sum of tower currents without including the correction factor of figure 43. The effect of this factor may be reflected in the comparison between curves 1 and 4 of figure 44, in that Rokkaku's is greater than Lewis and Foust's.

Figure 44 also contains data relating to strokes to tall objects, that of McEachron's being to the 1,250-foot Empire State Building in New York, N. Y. Wagner, McCann, and Beck's curve represents data to objects of varying heights all of which are considerably lower. Neither of these curves involves the errors discussed previously as the total stroke current passed through a single conductor. A comparison of McEachron's curve data with those of strokes to transmission lines indicates a much greater

Table I. Data on Strokes to Lines of the Pennsylvania Water and Power Company[55]

Line	Length in Miles	Year	Recorded Strokes: In Year	Recorded Strokes: Average	Strokes Per 100 Miles: In Year	Strokes Per 100 Miles: Average
Safe Harbor-Westport-Takoma, 220 kv	91.8	1935	115		125	
		1936	108		118	
		1937	87		95	
		1938	54		59	
		1939	118		129	
				96		105
Safe Harbor-Riverside, 220 kv	50.5	1938	46		91	
		1939	45		89	
				46		90
Safe Harbor-Perrysville, 132 kv	31.5	1935	27		86	
	31.5	1936	69		219	
	31.5	1937	44		140	
	33.8	1938	56		166	
	33.8	1939	53		157	
				50		154
Holtwood-York, 66 kv	22.8	1936	31		136	
		1937	41		180	
		1938	15		66	
		1939	22		97	
				27		120
Holtwood-Coatesville, 66 kv	29.4	1936	30		102	
		1937	25		85	
		1938	68		232	
		1939	45		153	
				42		143
Holtwood - Baltimore, 66 kv (2 lines) and Philadelphia Road-Gunpowder, 110 kv	40 (of right-of-way)	1939	66	66	165	165

Weighted average for all lines is 120 strokes per 100 mile-years having magnitudes giving tower currents in excess of 2,400 amperes.

proportion of currents of low magnitude. This may be caused partly by the higher sensitivity of McEachron's instruments but more likely by the difference in mechanism of strokes to tall objects and the influence of tall projections from the earth in producing premature initiation of discharges.

Curve 7 of figure 44 was calculated by Norinder from a knowledge of the magnetic field disturbance produced by a stroke to open ground. An evaluation of the accuracy of this curve is difficult because it involves an assumption as to the stroke mechanism, distance to stroke, and direction and length of stroke path.

Curve (*a*) of figure 46 gives the per cent distribution of

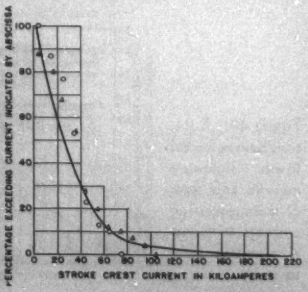


Figure 45. Stroke-current curve 1 of figure 44 reproduced for comparison with currents from lightning-rod measurements (circles) and overhead ground-wire measurements (triangles)

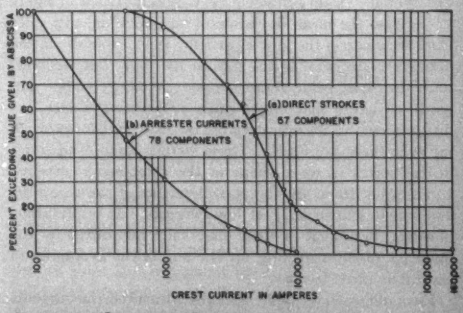


Figure 46. Percentage distribution curves of crest magnitude of individual components of surge currents, as obtained by Wagner, McCann, and Beck[65]

Table II. Outages Due to Lightning for Lines Without Ground Wires

Line	Kv	Length of Line	Years Covered	Total Outages	Outages Per 100 Miles Per Line-Year
Interstate Power Co., Clinton-Dubuque[29]	66	54	6	27	7
Pa. Water & Power Co., Holtwood-York[29]	66	23	11	213	84
Various lines in United States and Canada[30]					
16-A, wood	110	79.4	6		24
20-A, steel	140	148.0	10		5.6
23-BB, wood	132	39.8	8		37.2
31-B, steel	132	111.0	1		0
34-K, steel	110	38.3	10		61
34-O, steel	110	104.5	10		22.8
Steel[31]	Above 100	673	1929		21
		560	1930		14
Wood[31]	60–100	394	1929		26.6
Steel[31]	60–100	481	1929		23.5
		738	1930		25.9
Wood[32]	30–60	3,475	1929		34.6
		420	1930		30.4
Steel[32]	30–60	165	1929		17.6
		128	1930		14.2
Pa. Power & Light Co., steel[27]	220	41	8		25

67. For numbered references see list at end of article.

the crest magnitude of the individual components of direct strokes to objects varying in height from 300 to 585 feet. A comparison of this curve with curve 6 of figure 44 shows a larger proportion of small currents for the former. This is because only the maximum components of the multiple strokes were included in curve 6 of figure 44. The curves of figure 46 are probably more representative of conditions for judging arrester performance.

Crest currents as high as 220,000 amperes are indicated for strokes to lines. However, since these were obtained by adding currents in several towers they may be high. The highest current definitely known to have occurred somewhat exceeds 160,000 amperes, recorded at the Westinghouse recording station on the 585-foot smokestack of the Anaconda Copper Mining Company in Anaconda, Mont.

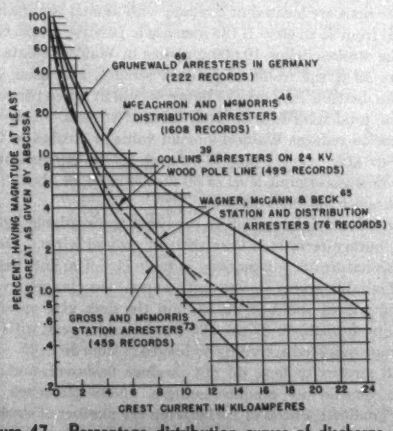

GRUNEWALD ARRESTERS IN GERMANY[69] (222 RECORDS)
McEACHRON AND McMORRIS[46] DISTRIBUTION ARRESTERS (1608 RECORDS)
COLLINS[39] ARRESTERS ON 24 KV WOOD POLE LINE (499 RECORDS)
WAGNER, McCANN & BECK[65] STATION AND DISTRIBUTION ARRESTERS (76 RECORDS)
GROSS AND McMORRIS STATION ARRESTERS[73] (459 RECORDS)
PERCENT HAVING MAGNITUDE AT LEAST AS GREAT AS GIVEN BY ABSCISSA
CREST CURRENT IN KILOAMPERES

Figure 47. Percentage distribution curves of discharge currents in lightning arresters

Arrester Currents. Crest magnitudes of arrester discharge currents, summarized in figure 47, are considerably smaller than those occurring on transmission lines. Those in station arresters, in general, are smaller than those occurring in distribution arresters. The maximum crest current measured in station arresters is 15,000 amperes and in distribution arresters approximately 30,000 to 40,000 amperes. The latter figure has been estimated since the maximum range of the recording instruments was

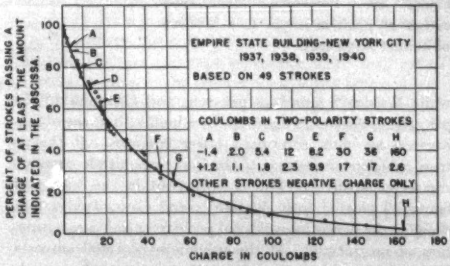

EMPIRE STATE BUILDING–NEW YORK CITY
1937, 1938, 1939, 1940
BASED ON 49 STROKES
COULOMBS IN TWO-POLARITY STROKES
A B C D E F G H
−1.4 2.0 5.4 12 8.2 30 36 160
+1.2 1.1 1.8 2.3 9.9 17 17 2.6
OTHER STROKES NEGATIVE CHARGE ONLY
PERCENT OF STROKES PASSING A CHARGE OF AT LEAST THE AMOUNT INDICATED IN THE ABSCISSA
CHARGE IN COULOMBS

Figure 48. Frequency of occurrence of stroke charge as measured by McEachron,[71] based largely on low-speed oscillographic data

25,000 amperes. Other data pertinent to the magnitude of arrester discharge currents are discussed later.

CHARGE

Wilson[9] has estimated that the average charge lowered by a discharge to open ground is from 10 to 50 coulombs. Figure 48 gives data on charge for strokes to the Empire State Building by McEachron, which indicate values in excess of 160 coulombs. In the investigations of Wagner, McCann, and Beck charges in direct strokes to tall objects of lower height ranged from 4 to 60 coulombs. Probably on the average the charge lowered increases with the height of the object. Charges exceeding one coulomb were found to be rare for arrester service.

POLARITY

Direct strokes of a given polarity produce surges of the same polarity, but induced surges are of opposite polarity. Schonland, Hodges, and Collins[17] state that all their electric field measurements indicated negative-polarity strokes; that is, they lowered negative charge to ground. All 58 strokes recorded to the Empire State Building were initially negative; only 3 of the 27 recorded with the crater-lamp oscillograph reversed their polarity. Of the 12 direct strokes recorded by Wagner, McCann, and Beck[65] all were initiated by negative discharges. Only two had subsequent positive components.

Lewis and Foust[66] state that 7 per cent of their records of strokes to transmission lines were of positive polarity,

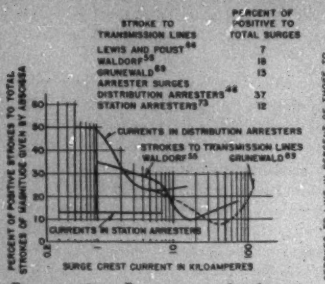


Figure 49. Percentage distribution curves of positive surges as a function of current magnitude

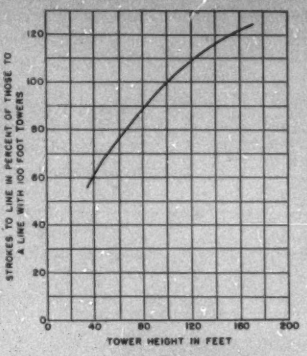


Figure 50. Probable variation of strokes to line as a function of height[76]

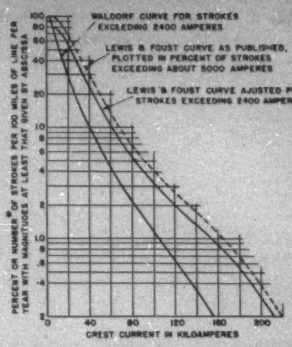

WALDORF CURVE FOR STROKES EXCEEDING 2400 AMPERES
LEWIS & FOUST CURVE AS PUBLISHED, PLOTTED IN PERCENT OF STROKES EXCEEDING ABOUT 5000 AMPERES
LEWIS & FOUST CURVE AJUSTED FOR STROKES EXCEEDING 2400 AMPERES
PERCENT OR NUMBER* OF STROKES PER 100 MILES OF LINE PER YEAR WITH MAGNITUDES AT LEAST THAT GIVEN BY ABSCISSA
CREST CURRENT IN KILOAMPERES

Figure 51. Probability curves of crest currents in lightning strokes to transmission lines

*Based on 100 strokes to line per 100 miles of line per year

while Waldorf[58] found 18 per cent and Grunewald,[69] 14 per cent. Waldorf's figure may be higher than the others because his data comprised lower currents. If this is true, a higher percentage of the lower-magnitude currents should be positive. This is borne out in the curves of figure 49 plotted from Waldorf's and Grunewald's data showing the percentage of total positive currents as a function of magnitude. At the minimum of 1,000 amperes Waldorf's data show that about 35 per cent of the records are positive, and Grunewald's, with a minimum of 5,000 amperes, show about 24 per cent.

Possibly currents as great as 5,000 or 10,000 amperes can be produced in towers by induced strokes, and they may be the cause of the higher percentage of positive records in the lower current range.

The studies of McEachron and McMorris show that 63 per cent of all their records of currents in distribution arresters are negative and 37 per cent positive, while Gross and McMorris found that for the station arresters 88 per cent were negative and 12 per cent positive. The curves of figure 49 plotted from these data show that for station arresters, the polarity is independent of current magnitude while for distribution arresters the number of positive discharges decreases with increase in current magnitude.

It is interesting to compare these results with the voltage measurements made on 4-kv distribution circuits by Halperin and McEachron, the results of which are shown in figure 30. If these voltages had appeared across 4-kv arresters with an impulse breakdown voltage of about 40 kv, the voltage curves for urban circuits indicate that 22 per cent of the arrester discharge currents would have been positive, and the curves for rural circuits indicate a figure of about 35 per cent. If these voltages had appeared on a 20-kv circuit with arresters having an impulse breakdown voltage of about 75 kv, no positive discharge currents would have been produced by the urban circuits and 27 per cent would have been produced by the rural circuits. The increase in positive discharge currents recorded in distribution arresters probably is due to induced surges. Quite likely they are greater on the lower-voltage circuits,[65] and greater the more exposed the lines, thus permitting higher magnitudes of induced surges.

NUMBER OF STROKES TO TRANSMISSION LINES

Of particular importance in evaluating lightning performance of a transmission line is knowledge of the probable number of strokes to it. Waldorf[58] presents valuable data on this subject from his surge-crest-ammeter studies on lines of the Pennsylvania Water and Power Company with voltage ratings ranging from 66 to 220 kv, as he had placed magnetic links on every tower. These data are summarized in table I and show a maximum variance in the number of strokes per 100 miles of line per year of from 59 to 232. The maximum variance for any line over the five-year period studied was from 85 to 232 and the variance of the average for each line over the five-year period was from 90 to 165. The weighted average of the data according to length of line and years considered is 120. These lines are located in a region with annual isoceraunic levels from 35 to 40. If the increase in positive proportion of the strokes below 10,000 amperes in Waldorf's data of figure 49 is the result of induced strokes, and using his stroke distribution curve of figure 44, about seven per cent of the total records arise from induced strokes. This assumption reduces Waldorf's mean value of strokes to the line to 112. Converting this figure to the conventional standard isoceraunic level of 30 results in 96, or about 100 strokes per 100 miles per year.

Additional information is provided by available lightning outage records of lines without ground wires. Data of this nature are summarized in table II. The lines listed in this table are in regions with annual isoceraunic levels ranging from about 30 to 55, and the data give outages varying from 15 to 87 per 100 line-miles per year, with an average weighted according to length of from 30 to 35.

All strokes to lines do not produce flashover, and all flashovers do not produce outages. Data published by Bell[67] indicate a ratio of 1.5 between the number of strokes producing flashover and those producing outage on the portion of the 220-kv Wallenpaupack-Siegfried line of the

Table III. Tabulated Data on Five Stroke-Current Oscillograms Obtained by Stekolnikov and Valeev[22]

Oscillogram number	1	2	3	4	5
Crest value of current in kiloamperes	30	18	31	17	30
Front of wave in microseconds	8	10	3.5	10	1.5–2.0
Maximum rate of rise of current in kiloamperes per microsecond	6.6	7.6	25	4.0	
Mean rate of rise in kiloamperes per microsecond	3.8	1.8	9.0	1.7	
Measurable duration in microseconds	35	45	30	23	

Polarity—all negative but last one, which was oscillatory.

Pennsylvania Power and Light Company that does not have ground wires. Information supplied by I. W. Gross on the 132-kv lines of the American Gas and Electric Company (which have ground wires) indicates a ratio of 1.27. This ratio probably varies with the system, being higher the longer the flashover path and the lower the fault current. An estimate of the number of strokes producing flashover on a given line without ground wires can be obtained from, say, curve 3 of figure 44, together with a knowledge of the surge impedance of the line and its insulation level. The voltage produced by a stroke to a phase conductor should be equal to the product of one-half the stroke current and the surge impedance of the conductor. Estimates of the probable mean ratio between outages and strokes to lines without ground wires for the lines listed in table II indicate a mean value for strokes to lines of about 60 per 100 line-miles per year. This is, of course, only an estimate, and probably the figure of 100 based on Waldorf's data should be used in a region of isoceraunic level of 30.

Lightning-performance studies of lines made in the laboratory with models by Wagner, McCann, and MacLane[76] indicate that the number of strokes to the line is a function of tower height as shown in figure 50. However, no such trend is shown in Waldorf's data. This is probably because other factors such as line locations cause a greater variance. Thus the average value of 100 should apply to all practical values of tower height.

It is then possible to plot Waldorf's percentage distribution curve in figure 44 as a probability curve giving the number of strokes of a given magnitude to be expected. This is shown in figure 51 together with the corresponding curve of Lewis and Foust drawn as published, and also drawn adjusted to the same minimum current as used by Waldorf. The data of this figure are on a line basis and not a circuit basis; the number of strokes to a line is independent of the number of circuits comprising it.

NUMBER OF SURGES DISCHARGED BY LIGHTNING ARRESTERS

Figure 52 shows curves compiled from the data of Gross and McMorris[73] and McEachron and McMorris[46] on the expected number of surges of a given magnitude to be discharged per single-phase arrester per year. The curves indicate an average of 0.8 surge exceeding 300 amperes for station arresters, but only 0.4 for all distribution arresters. Rural distribution arresters experience more than urban arresters, because of the greater density and better shielding of urban arresters. Rural distribution arresters, although having fewer surges than station arresters, are required to discharge higher currents.

Figures 53 and 54 show the distribution of duty among individual arresters. Figure 53, drawn from the data reported by Gross and McMorris, shows that for a group of station arresters 32 per cent discharged no surges in four years, only 25 per cent discharged two, and the maximum number discharged was 3.84 per single-phase arrester per year. The curve of figure 54 indicates more discharges. This may not be typical of duty on an average group of arresters, as the locations were chosen because experience indicated that they were subject to severe lightning conditions.

The effect of line insulation on arrester duty is shown in figure 55. Wood-pole lines with no ground wires, as would be expected, produce more severe duty.

WAVE SHAPE OF LIGHTNING CURRENTS

An inherent difficulty in measuring the total current in direct strokes is the necessity of obtaining a point at which the current is totalized. This has led to collecting the current in a single mast. If, however, these masts are on low objects such as transmission towers, the chance of a

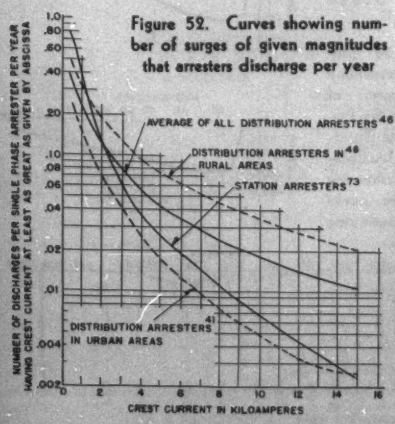


Figure 52. Curves showing number of surges of given magnitudes that arresters discharge per year

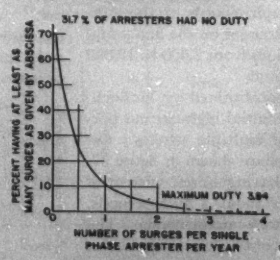


Figure 53. Distribution of duty on station arresters, data from Gross and McMorris[73] on 85 three-phase banks for four-year period

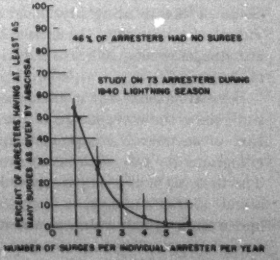


Figure 54. Duty on individual arresters from data obtained by Wagner, McCann, and Beck[65]

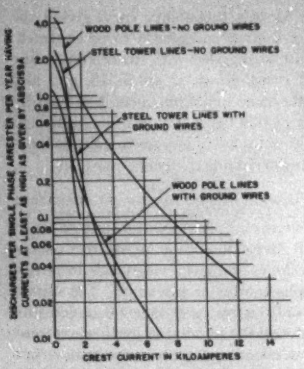

WOOD POLE LINES-NO GROUND WIRES
STEEL TOWER LINES-NO GROUND WIRES
STEEL TOWER LINES WITH GROUND WIRES
WOOD POLE LINES WITH GROUND WIRES
DISCHARGES PER SINGLE PHASE ARRESTER PER YEAR HAVING CURRENTS OF LEAST AS HIGH AS GIVEN BY ABSCISSA
CREST CURRENT IN KILOAMPERES

Figure 55. Effect of line construction on number and magnitude of station - arrester discharge currents, Gross and McMorris[73]

particular point being struck is small. On the other hand, if tall objects such as buildings and smoke stacks are utilized, more records for a single installation can be obtained but it is always uncertain how much such strokes differ from those to lower objects, as dealt with in the power-transmission problem. It is known, for example, that the initial streamers, the direction of propagation, and other vital characteristics differ in the measured discharges at the Empire State Building from those elsewhere. In spite of these uncertainties, most direct-stroke data have been obtained on tall objects.

Stekolnikov and Valeev[22] in Russia in 1936 obtained the first oscillograms of the current in direct strokes. These studies were made with a balloon attached to a metal cable and flown at altitudes between 500 and 800 meters during a thunderstorm. Resistance shunts were connected directly in the cable circuit for a cathode-ray oscillograph and a high-speed rotating klydonograph. In addition, a short horizontal antenna about 20 meters above the ground was used with a cathode-ray oscillograph and a rotating klydonograph. During the lightning season only two storms occurred near the lightning station, but six strokes to the vertical antenna were recorded, five in one storm. The cathode-ray oscillogram of one of these is shown in figure 56, and data on the five strokes that could be analyzed are given in table III. These records indicate fronts of from $1^1/_2$ to 10 microseconds and rates of rise of from 1.8 to 9 kiloamperes per microsecond. The maximum duration as recorded by the oscillograph was not over 50 microseconds, but the instrument was not very sensitive. Some of the rotating klydonograph records of the individual components of the induced surges on the horizontal antenna, however, indicate durations from 2,600 to 10,000 microseconds.

Several cathode-ray oscillograms obtained by McEachron[77] show the wave shape of the initial high-current portion of successive components of multiple strokes. Oscillograms for two of these strokes are shown in figure 57. The first (*a*) is of a single stroke having a crest current of about 15,000 amperes, a front of about 4 microseconds, and a time to half value of about 75 microseconds. The second two oscillograms (*b*, *c*) are of two components of a multiple stroke. Each has crest values of about 20,000 amperes, fronts of about 10 microseconds, and times to half value of about 70 microseconds.

McEachron concludes that the current between components of a stroke is continuous, although in many cases it may be only a few amperes. An example of a crater-lamp oscillogram showing the presence of such currents between successive peaks is given in figure 58. This oscillogram is also interesting in that it confirms an essential difference between the types of discharge to high and low objects. The vast majority of the discharges to the Empire State Building were initiated by upward streamers from the building, and until this streamer tapped a concentration of charge in the cloud the record indicated a low magnitude of current as shown in figure 58 for the first few tenths of a second.

Wagner, McCann, and Beck[45] have presented data obtained with the fulchronograph on objects varying between 300 and 600 feet in height. Of twelve records obtained only one shows evidence that the discharge was

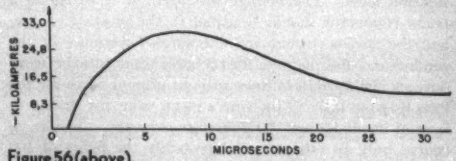


Figure 56 (above). Cathode-ray oscillogram of current in lightning stroke to captive balloon[22]

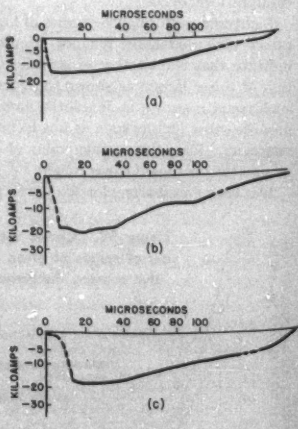
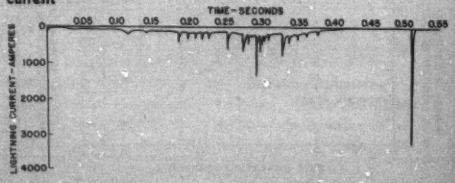


Figure 57 (right). Cathode-ray oscillograms of the currents in two strokes to the Empire State Building[77]

Figure 58 (below). Crater-lamp oscillogram of stroke to the Empire State Building by McEachron,[77] showing successive peaks and continuing current



initiated by an upward streamer. This record was obtained at the Cathedral of Learning of the University of Pittsburgh, Pa., and is shown in figure 59a. This figure also shows fulchronograms of direct strokes of the more conventional type. The Anaconda record 29 represents the maximum measured lightning current for which the measured current flowed through a single conductor. Record 34 has the largest number of components of the fulchronograms obtained in this investigation, and shows, furthermore, that the maximum component does not always occur near the beginning of the stroke. A similar phenomenon was observed with photographic studies.[65] Several fulchronograms of current discharged by arresters are shown in figure 60.

WAVE SHAPE OF INITIAL HIGH-CURRENT PORTION OF SURGE

Time to Half Value. Fulchronograms[66] have been obtained giving the current wave shape and duration of 12 direct strokes having 57 components, and of 60 arrester discharges having 78 components. Of the direct-stroke records, the times to half value of the initial high-current portions varied from 25 to 100 microseconds, with an average of 50 microseconds. The times to half value of the arrester surges varied from 25 to 350 microseconds. Eliminating record 48 of figure 60, the times to half value range from 25 to 80 microseconds, with an average of 47. The character of the tail of the high-current components is the same in both direct-stroke and arrester-discharge records. These data are summarized in figure 61.

Similar data obtained by McEachron[63] by means of the cathode-ray oscillograph are summarized in figure 62.

Wave Fronts. The results of Stekolnikov and Valeev on direct strokes as summarized in table III indicate wave fronts of from 1.5 to 10 microseconds. Figure 63 summarizes data obtained on the Empire State Building.[63]

Table IV gives the results of measurements made with the magnetic surge-front recorder on direct-stroke currents, arrester discharge currents, and a transmission-line tower current.[65] These data indicate a lower limit of 0.5 and an upper limit of 20 microseconds. The lower limit, however, is quite doubtful because the presence of multiple strokes impaired the indication. The highest average rate of current rise measured in a direct stroke in these studies is 7,600 amperes per microsecond for a stroke with a crest of 19,000 amperes. However, the transmission line tower current, which had a crest of 50,400 amperes, indicated an average rate of rise of 43,600 amperes per microsecond. The highest average rate of rise measured in an arrester discharge was 3,200 amperes per microsecond for a surge with a crest current of 5,100 amperes.

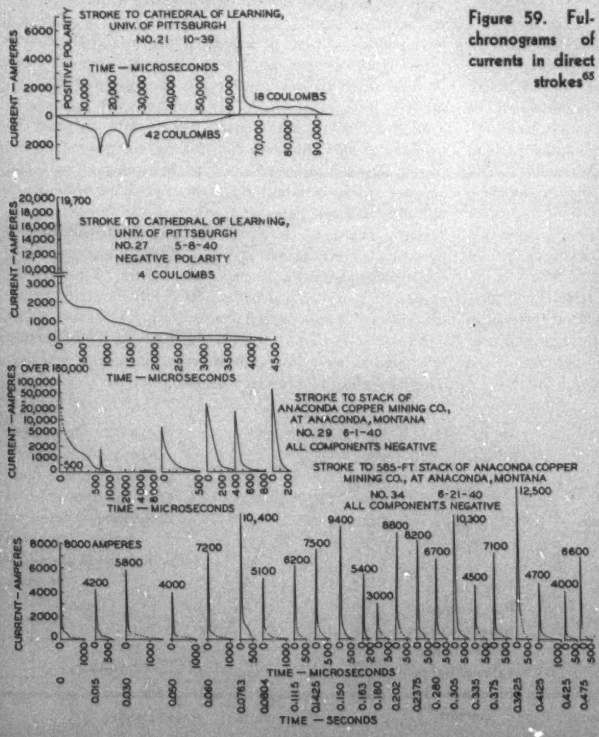

STROKE TO CATHEDRAL OF LEARNING, UNIV. OF PITTSBURGH NO. 21 10-39
CURRENT — AMPERES
POSITIVE POLARITY
TIME — MICROSECONDS
18 COULOMBS
42 COULOMBS
STROKE TO CATHEDRAL OF LEARNING, UNIV. OF PITTSBURGH NO. 27 5-8-40 NEGATIVE POLARITY
4 COULOMBS
OVER 180,000
STROKE TO STACK OF ANACONDA COPPER MINING CO., AT ANACONDA, MONTANA NO. 29 6-1-40 ALL COMPONENTS NEGATIVE
STROKE TO 565-FT STACK OF ANACONDA COPPER MINING CO., AT ANACONDA, MONTANA NO. 34 6-21-40 ALL COMPONENTS NEGATIVE
8000 AMPERES
TIME — SECONDS

Figure 59. Fulchronograms of currents in direct strokes[65]

Figure 64 gives percentage distribution curves on the rate of rise occurring on the front of the wave. Berger's measurements are of currents in transmission-line towers. The highest rate of rise that he recorded was between 30,000 and 40,000 amperes per microsecond. However, the crest currents associated with the records did not exceed 40,000 amperes. Norinder's values are questionable, as they were estimated from measurements made of the magnetic fields produced by lightning strokes. McEachron's data represent the effective rate of rise of strokes measured with the cathode-ray oscillograph.

CHARACTERISTICS OF THE LONG-DURATION TAILS

The records obtained on the long-duration portion of direct strokes indicate that their character varies over wide limits. Aside from the strokes of continuing character recorded to tall objects,[65,71] the fulchronograms[65] of direct strokes indicate component durations of between 50 and 20,000 microseconds. The upper curve of figure 65 shows the measurable duration of individual components of 57 direct strokes measured with the fulchronograph.

Figure 65 also shows that arrester-current records have considerably less evidence of long-duration tails. Of the

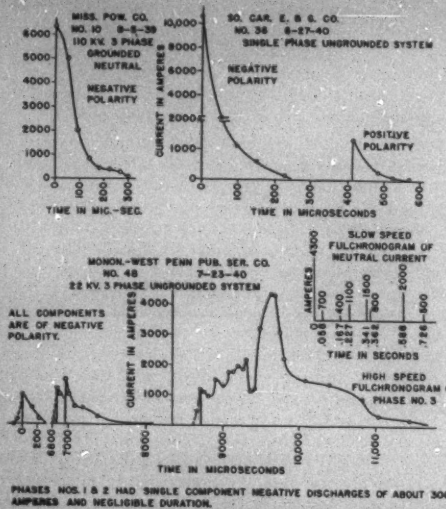


Figure 60. Fulchronograms of lightning-arrester discharge currents[65]

82 discharge records obtained, for only 14 did the surge the last longer than 300 microseconds. One of these is record 48 of figure 60. As shown by Bergvall and Beck[25] power transformers on grounded-neutral systems should be able to absorb the long-tail portion of the wave to an appreciable degree, if a sufficiently low impedance path to ground is provided. Distribution transformers should perform this function to a lesser degree. Thus, under these conditions, the arresters and transformers tend to protect each other. The arrester takes the high-current portion of the surge, which is injurious to the transformer; and the transformer the long-duration portion, which is injurious to the arrester. This is verified by the fact[65] that the 14 long-duration records were obtained on systems in which the protective value of the transformer ground connection is absent, although only about 30 per cent of the arrester records were obtained on this type of circuit.

Table IV. Records Obtained With Magnetic Surge-Front Recorders by Wagner, McCann, and Beck[65]

Record Number	Polarity	Crest Current, Amperes	Surge Front, Microseconds	Average Rate of Rise, Amperes Per Microsecond
Currents in direct strokes				
24	Neg.	19,000	2.5	7,600
34	Neg.	3,000–12,500	0.5–9.6*	1,300–6,000*
59	Neg.	1,000–3,300	0.5–19.0*	174–2,000*
60	Neg.	325–6,800	0.5–6.0*	1,140–2,000*
Currents in common grounds of three-phase arrester banks				
5	Neg.	100	More 10	Less 10
55	Neg.	1,600	2	800
30	Pos.	500	1	500
41	Neg.	500	1.1	450
31	Pos.	600	More 6	Less 100
42	Pos.	825	More 20	Less 40
38	Pos.	1,100	3.9	280
47	Neg.	2,300	6	380
45	Neg.	200	More 10	Less 20
58	Neg.	5,100	1.6	3,200
48	Neg.	400–4,300	(0.5–20)*	500–2,600*
Transmission-line tower current				
66	Neg.	50,400	1.16	43,600

*These values indicate the limits within which the true values lie due to inaccuracies introduced by multiple strokes.

Further evidence of the influence of the system ground on surge duration is found in the field experience that has been gained in the past three years with a new type distribution arrester.[66] Of 27,000 arrester years of operation on four-wire systems in which the neutrals of the source transformers are grounded with the neutral brought out to the distribution transformers being protected, no failures have occurred. For systems with the source grounded but with the neutral not brought out and the primary of the protected transformer not grounded, the record shows 7 failures caused by lightning out of 8,500 arrester years, or 0.082 per cent. On delta systems 11 lightning failures have occurred in 4,500 arrester years, giving a performance of 0.24 per cent. This result can be explained only by the presence of long-duration surges.

A further significant fact is that 16 of the 18 failures occurred on four systems having only 1,078 arrester years' experience. These systems, in addition to being either delta- or wye-connected with the protected transformer ungrounded, were in regions of very high soil resistivity. This indicates that strokes in regions of high soil resistivity

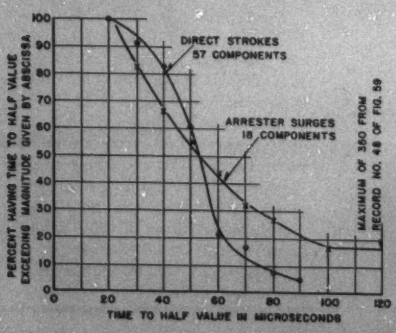


Figure 61. Percentage distribution curves of time to half-value of lightning-stroke currents[65]

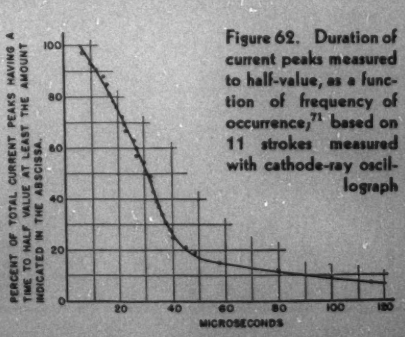


Figure 62. Duration of current peaks measured to half-value, as a function of frequency of occurrence,[71] based on 11 strokes measured with cathode-ray oscillograph

may have longer-duration components than those in regions of low soil resistivity.

CONCLUSION

As a result of the investigations described, certain characteristics of lightning may be said to be quite definitely known. Among these are:

1. Mechanism of the discharge.
2. Polarity.
3. General wave shape.
4. Number of components in the discharge.
5. Time intervals between components of discharges.
6. Total stroke durations.
7. Crest magnitude of stroke current at ground, of tower currents, and of currents discharged by lightning arresters.

On the other hand, many questions are still only partially answered. Thus,

1. Thunderstorms appear to follow more or less definite paths as influenced by local terrain, which produces great localized variations in storm and lightning-stroke density. The only information available as to the density of strokes is that distributed by the Weather Bureau, which pertains only to the number of storm days, and is based upon aural indications. The Bureau data do not take these local conditions and line locations with regard to them into consideration.

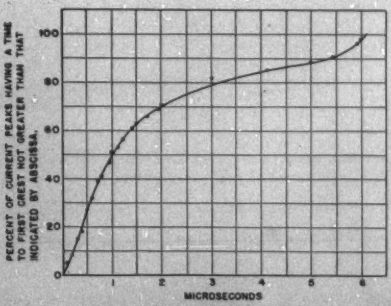


Figure 63. Time to first crest of current peaks, as a function of frequency of occurrence,[71] based on cathode-ray oscillograms of 13 strokes

2. Of the half-dozen proposed theories of charge formation, none explains completely all the factors involved.

3. The length of the stroke channel, that is, the height of the charge centers above earth, and the distribution of charge and current in the channels are still insufficiently known.

4. Earth resistivity and geological structure appear to influence the duration and possibly the crest magnitude of stroke discharges, but insufficient information is available to determine the extent.

5. Tall objects unquestionably affect the initial streamers and it is likely that the subsequent discharge is also affected.

6. The extent to which current at the ground flows between the individual components is still somewhat questionable.

7. The initial rates of rise of stroke currents and voltages encountered on systems are still worthy subjects of research.

8. More direct evidence is required to determine whether some of the recorded tower currents are due to induced effects.

It is apparent, therefore, that although considerable progress has been made in lightning research, many questions still remain for further investigation.

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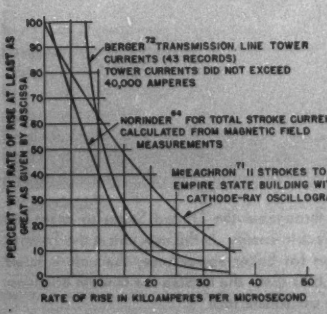
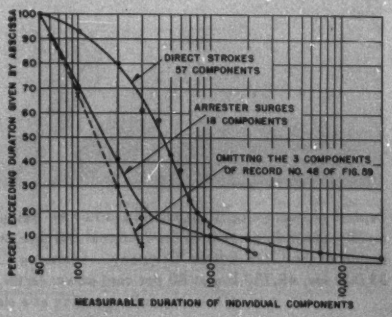


Figure 64 (left). Percentage distribution curves of rate of current rise on fronts of lightning surges

Figure 65 (right). Percentage distribution curves of duration of individual components of lightning-surge currents[63]



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Westinghouse Photo

Typical of steam-electric generating units now being installed in power stations throughout the United States to meet the rapidly expanding needs of the National Defense program for more and more electric energy, is this new unit at the Toronto station of the Ohio Edison Company. Featuring "smooth" design which makes for better appearance, the unit is rated 35,000 kw, 42,750 kva at 80 per cent power factor, 11.5 kv, and operates at 3,600 rpm; the turbine is a tandem condensing unit operating at a steam pressure of 800 pounds per square inch

Institute Activities

Post-Defense Plans Discussed at Pacific Coast Convention

A SUCCESSFUL Pacific Coast convention was held in the Canyon Hotel at Yellowstone National Park, August 27–29, 1941. The meeting was attended by 321 members and guests, a total which exceeds by 13 the average total attendance for the past 17 Pacific Coast conventions, not including those combined with the summer conventions. A conference on "After the Emergency, What?" was the feature of the program, which also included three technical sessions, two technical conferences, one general session, two student sessions, as well as a dinner and conference on student activities, and an informal convention dinner and dance.

"AFTER THE EMERGENCY, WHAT?"

The conference was opened at 9:30 a.m., Friday, August 29, by L. R. Gamble, presiding, who after briefly introducing the subject called on President Prince as the first speaker.

President Prince presented and analyzed data for a plan of national economy intended to result in a higher standard of living after the Defense Program is over. Briefly, the plan proposed to maintain as a peacetime effort the maximum gross national production resulting from the defense effort. This would result in keeping all of the people gainfully employed and increase their purchasing power. The mere subsistence income of 11,000,000 families, which was under $1,000 in 1940, could be raised to $1,500 and that of 7,000,000 other families between $1,000 and $1,500 could be raised to $1,500. The margin of income over subsistence would be increased. President Prince showed that from 1920 to 1940 the margin of income above subsistence increased in almost direct proportion to the use of electric power in industry. As a result of the increased margin of income over subsistence he estimated that approximately 85,000,000,000 kilowatt hours of commercial light and power sales would be required. The contemplated higher standard of living would permit many families to purchase automobiles, radios, electric appliances, and other consumer durable goods for the first time. These factors, combined with the accumulated deficiency resulting from present defense curtailment in production of consumer durable goods and home construction, were described as the elements that would contribute to better living conditions for all after the Defense Program comes to a close.

By means of bar charts President Prince illustrated the division of gross national output in billions of dollars for the years 1940 and the estimated quantities for the years 1943 and 1946. He also illustrated how the demand for electrical products in 1943 could be estimated and the data applied, for example, to the equipment to be made by the General Electric Company.

In conclusion, President Prince urged that everyone should make a plan showing how the transition from a wartime to a peacetime economy should be made; that from all such plans submitted an over-all plan could be put together that would bring about the highest standard of living the country has ever known. He explained that such a plan would be "everybody's idea" when finished, having been contributed to by all the engineering societies, firms, bankers, economists, and others interested.

Inasmuch as a proposal of a plan for national economy would require considerable study, most of the discussion centered about the psychological factors, the ways and means of disseminating the plan to the public, and the suggestions to form a board of experts and to work with other groups of engineers. L. F. Hunt suggested that consideration be given to the modernization of equipment, such as oil-circuit breakers, generators, etc., and he emphasized that engineers should be guided by facts and do less guessing. R. B. Hubbard advised that the Colorado Engineering Council in Denver had already started work on a plan and, with a view toward working together, asked if other groups were making similar plans. Professor E. W. Schilling referred to an article in the publication of the National City Bank of New York, July issue, entitled "The Over-Savings Controversy," which contained quotations from testimony and the book by Mordecai Ezekiel. Another speaker, with a view toward study of the periods after the first World War, referred to the work of Doctor W. E. Wickenden entitled "The Second Mile." Some 70 or more people attended the meeting and 13 took part in the discussion.

Analysis of Attendance at 1941 Pacific Coast Convention

Classification	District 8	District 9	District 10	Miscellaneous	Totals
Members	31	62	1	39	133
Men guests	6	19	1	14	40
Women guests	34	60	1	43	138
Enrolled Students	7	4			11
Totals	78	145	3	96	322

Pacific Coast Convention Attendance—1921–1941

Year	Location	Attendance
1921	Salt Lake City, Utah	*
1922	Vancouver, B. C.	235
1923	Del Monte, Calif.	252
1924	Pasadena, Calif.	363
1925	Seattle, Wash.	408
1926	Salt Lake City, Utah	250
1927	Del Monte, Calif.	250
1928	Spokane, Wash.	250
1929	Santa Monica, Calif.	440
1930	Portland, Ore.	300
1931	Lake Tahoe, Calif.	247
1932	Vancouver, B. C.	300
1933	(No Pacific Coast convention)	
1934	Salt Lake City, Utah	232
1935	Seattle, Wash.	260
1936	Pasadena, Calif.	*
1937	Spokane, Wash.	266
1938	Portland, Ore.	454
1939	San Francisco, Calif.	*
1940	Los Angeles, Calif.	465
1941	Yellowstone Park	322

*Combined with summer convention.

GENERAL SESSION

At the general session, held Thursday, August 28, W. H. Reif, convention chairman, gave an address of welcome. President D. C. Prince, presiding at the session, introduced the speakers, and praised the co-operation of local industries in making the convention possible. Doctor C. M. Bauer, chief naturalist of Yellowstone National Park, spoke on "Wonders of Yellowstone Park," emphasizing the policy of keeping the Park as nearly in its natural state as possible. Robert H. Fletcher, director of publicity, Montana Power Company, presented an enlightening and colorful account of Montana's development from the time of the Lewis and Clark expedition to the present. About 225 persons were present at the general session.

STUDENT DINNER AND CONFERENCE

The conference on student activities was held on Wednesday, August 27, preceded by a dinner. Chairman B. H. Hull, who presided, explained that the purpose of the conference was to help the Branch counselors conduct their meetings during the coming year. President Prince addressed the meeting on the evolution in industry and referred to the use of machine calculations. He explained that the industrial process has become subdivided so as to require the close co-operation of all and that it has become increasingly important to train people to think in the terms of those with whom they will come in contact.

National Secretary Henline described the growth of the Institute from 1902–03, when the plan for Sections and Branches was put into effect up until the present. He referred to the fact that the first conference on student activities was held in Salt Lake City 15 years ago in connection with a Pacific Coast convention. Vice-President Smith pointed out that the advantages of student enrollment existed even for those going into Army service. He explained that the Institute was endeavoring to take on broader aspects, such as economics.

The chairman of each Branch present gave a short talk on the types of meetings arranged during the year in order that the other chairmen might profit by such an exchange of information for the planning of future programs. Professor C. F. Dalziel, chairman of District 8 committee on student activities, presented a report on the meeting

(*Continued on p. 503*)

Southern District Meeting Will Be Held at New Orleans

THE AIEE Southern District meeting will be held at New Orleans, La., December 3–5, 1941, with headquarters at the St. Charles Hotel. Presenting a stimulating program, this meeting will also provide an opportunity of enjoying southern sunshine and hospitality and of seeing one of America's most fascinating cities. Besides the interest of its historic places, New Orleans presents a cross-section of southern industry.

A technical program of varied interest is being planned with a special view to developing data from southern electrical industries. The committee reports tentative scheduling of ten technical sessions, divided into three subject groups: petroleum, transmission and distribution, and industry, in each of which papers of timely interest are expected to be presented.

TRIPS AND OTHER FEATURES

Scheduled for two afternoons are trips offering a choice among features of varied interest. A tour will be made of New Orleans' French Quarter, the Vieux Carre, of which Royal Street (shown at extreme left) is typical in its width, its French and Spanish houses, and its wrought-iron balconies. A river and harbor inspection trip will include the waterfront (shown at bottom of page), such activity as cotton-loading at one of the world's leading cotton ports (above), and the Huey P. Long bridge over the Mississippi River (lower left) which provides for railway, motor, and pedestrian traffic on its more than four miles of length. Water and sewage facilities of New Orleans will be inspected on another trip, and still another will visit one of the largest sugar-grading and refining plants in the world, that of the Godchaux Sugar Company (top, left) at Reserve, La., about 30 miles north of New Orleans.

Provisions also have been made for student participation in the program. An extensive social program with entertainment for women guests is being arranged.

Future AIEE Meetings

South West District Meeting
St. Louis, Mo., October 8–10, 1941

Southern District Meeting
New Orleans, La., December 3–5, 1941

Winter Convention
New York, N. Y., January 26–30, 1942

(*Continued from p. 501*)

of all Student Branch counselors held during the summer convention in Toronto last June.

H. F. Lickey, Washington State College, was elected chairman of the District 9 committee on student activities. Branch Counselor J. C. Clark of the University of Arizona, was elected chairman, Branch Counselor F. W. Maxstadt of the California Institute of Technology secretary, of District 8 committee on student activities.

TECHNICAL SESSIONS

Three technical sessions were held, on protective devices, power transmission and distribution, and selected subjects. In the conference on circuit breakers held immediately after the session on protective devices the showing of motion pictures by H. E. Strang on the opening and closing of a high-speed 138-kv air-blast circuit breaker proved to be an added attraction.

STUDENT SESSIONS

Student sessions were held on Wednesday morning and Friday afternoon with Curtis E. Abbott and Jerome Johnson presiding, respectively. The following papers were presented at these sessions.

Wednesday, August 27

AN ELECTRICAL METHOD FOR AUTOMATIC MUSIC TRANSPOSITION. **Richard E. Hodges,** University of Southern California

DESIGN OF THE LOW-FREQUENCY CHARACTERISTICS OF VIDRO AMPLIFIERS. **William H. Huggins,** Oregon State College

Friday, August 29

DESIGN AND CONSTRUCTION OF A SEVEN THOUSAND-FOOT POWER LINE SPAN. **R. W. Retherford,** University of Idaho

THE KLYSTRON AS A SOURCE OF MICRO-WAVES. **R. A. Soderman,** Stanford University

SUB-HARMONICS IN NON-LINEAR CIRCUITS. **Otway O. Pardee and Theodore V. Zaloudek,** University of Washington

ELECTRICAL DISCHARGES THROUGH RESTRICTED AREAS. **Messrs. Thompson and Bayer,** University of Utah

AN ELECTRIC HARMONIC WAVE ANALYZER. **Wilbur R. Morton and Gustave I. Oliver,** University of Santa Clara

OFFICERS' LUNCHEON

A luncheon of Section, District, and national officers was held on Thursday, August 28, at which Dan Young, manager of the Milwaukee Railroad Gallatin Gateway Inn, was the principal speaker

ENTERTAINMENT

An informal convention dinner and dance were held in the Canyon Hotel Thursday evening, August 28. During the meeting women guests attended a western tea, at which copper hats were given as souvenirs.

Among inspection trips planned for the AIEE South West District meeting, to be held at St. Louis, Mo., October 8–10, 1941, is a visit to Washington University, which will feature the University's new Cyclotron, housed in the Engineering Building. Campus and buildings are shown here as seen from the air

A fishing trip on Thursday morning, followed by a fish fry, proved popular and was repeated on Friday for women guests. Thursday afternoon children were taken on a bus tour in the Park, followed by dinner and an evening show in the Canyon Lodge. Horseback riding and hiking also were popular activities.

Abstracts • • •

TECHNICAL PAPERS are previewed in this section as they become available in advance pamphlet form. Copies may be obtained by mail by remitting price indicated to the AIEE order department, 33 West 39th Street, New York, N. Y.; or at five cents less per copy if purchased at AIEE headquarters or at AIEE convention or District-meeting registration desks.

The paper previewed in this issue will be presented at the AIEE South West District meeting, St. Louis, Mo., October 8–10, 1941.

Electrical Machinery

41-163—Short Circuits in Synchronous Machine Armatures; *R. A. Galbraith* (*A'38*). *25 cents by mail.* An approximate solution is obtained for the current in a short-circuited coil or group of coils in the armature of a synchronous machine operating under load. The solution is expressed as the sum of a series of harmonics whose terms are in geometric ratio. The results obtained are similar in form to those previously obtained for the short circuit of a complete phase winding, and they reduce to that for the single-phase short circuit in the limiting case when the coil group comprises a complete phase. An experimental check of the theory is given for the case of a short circuit of a single armature coil, and it is shown that close agreement is obtained between theory and test with respect to the fundamental component of current, though not with respect to the small higher harmonics of current.

Standards • • •

Supplement for "AIEE Standards No. 1"

Standards co-ordinating committee 4, under the chairmanship of P. L. Alger, has prepared a proposed supplement to Pamphlet No. 1, "Introduction to the AIEE Standards—General Principles Upon Which Temperature Limits Are Based in the Rating of Electrical Machinery and Apparatus" (usually referred to as AIEE Standards No. 1). This supplement, Pamphlet 1A, is en-

A Challenge

Mr. Institute Member:

Good results always challenge us to better results. The membership of the Institute reached such a high level last year, through your efforts of co-operation with the membership committees, that I am asking again for your full co-operation this year. NOW IS THE TIME to review your list of friends and acquaintances and send in any names of persons eligible for membership, thus getting off to a good start for the year. Your assistance is needed to maintain the upward trend of membership.

C. C. Brill

Chairman, National Membership Committee

titled "General Principles for Rating of Electrical Apparatus for Short-Time, Intermittent, or Varying Duty". It is issued for study and comment. In its final form, as a part of the present No. 1, it should serve as a guide in the preparation of standards for short-time rated or intermittent-duty apparatus of specific types or fields of use. Its provisions are not intended to be used for rating or testing any apparatus for which specific AIEE Standards are available. The following are the principal matters covered: output limitations, temperature limits for short-time rated apparatus, and service factors. Several alternative methods of rating are given, as follows: continuous rating method, load-factor method, nominal and specified overload method, duty-cycle method, short-time rating method, and service factor rating method. Copies of this pamphlet may be obtained without charge by writing H. E. Farrer, AIEE headquarters, 33 West 39th Street, New York, N. Y.

Personal • • •

C. R. Beardsley (A'08, F'30) manager, contract control and inspection department, Consolidated Edison Company of New York, Inc., New York, N. Y., has been appointed chairman of the AIEE committee on Institute policy for 1941–42. He has been a member of the committee since 1940 and is also serving on several special committees. He has served also on the Edison Medal and technical program committees. He was chairman of the special committee on model registration law 1937–39, until its functions were taken over by the committee on legislation affecting the engineering profession, of which he was a member 1937–41 and chairman 1939–41. He was a member of the board of directors from 1937 to 1941. Born December 19, 1885, at Bridgeport, Conn., Mr. Beardsley received the degree of bachelor of philosophy in electrical engineering from Yale University, 1905. From 1905 to 1911 he served in various capacities with the General Electric Company in New York and New Haven, and in 1911 became sales agent for the United Illuminating Company, Bridgeport, Conn. He joined Fred T. Ley and Company, Springfield, Mass., as electrical engineer, in 1918, and in 1923 became electrical construction engineer for the Brooklyn Edison Company, Brooklyn, N. Y. He was transferred to Consolidated Edison in 1938, and was made manager of the contract control and inspection department in 1939. He is the author of many technical articles.

L. R. Mapes (M'29, F'37) general manager, state area, Illinois Bell Telephone Company, Chicago, Ill., has been appointed chairman of the AIEE committee on planning and co-ordination for 1941–42. Mr. Mapes was born March 26, 1892, in Middletown, N. Y., and received the degree of electrical engineer from Columbia University in 1913. He entered the employ of the American Telephone and Telegraph Company in 1913, doing designing and consulting work for various branches of the company. In 1925 he became equipment and building engineer for the Illinois Bell Telephone Company, and in 1928 was made chief engineer for the Chicago area of the company. He became general manager of the state area in 1938. He was president of the Western Society of Engineers 1939–40. He is a director of the Institute and is also a member of the committee on communication. He formerly served on the committee on transfers.

E. C. M. Stahl (M'27) assistant manager, production department, Consolidated Edison Company of New York, Inc., New York, N. Y., has been appointed chairman of the AIEE headquarters committee for 1941–42. Mr. Stahl is also a member of the committee on power generation, and formerly has served on the committees on power generation (chairman 1938–40) and technical program. He was born March 10, 1891, in St. Paul, Minn., and received the degree of mechanical engineer from Cornell University in 1913. From 1913 to 1920 he was with the New York Central Railroad, except for a period during 1917–18 when he served as a captain in the United States Army coast artillery corps. He joined the Pittsburgh Transformer Company, Pittsburgh, Pa., in 1921, working on patent investigations for the company. In 1922 he became electrical field engineer for the Brooklyn Edison Company, Brooklyn, N. Y., and in 1927 was made assistant superintendent of the company's Hudson Avenue station. He was appointed engineer of tests in 1928, and became assistant operating superintendent about 1930. He was made operating superintendent in 1934, and in 1937 was transferred to the Consolidated Edison Company of New York, Inc., as assistant manager of production.

R. E. Hellmund (A'05, F'13) chief engineer, Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa., has been appointed chairman of the AIEE Lamme Medal committee for 1941–42. Born at Gotha, Germany, February 2, 1879, Mr. Hellmund received the degree of electrical engineer from the Technical College of Ilmenau, Germany, in 1899. He also did post-graduate work at the University of Charlottenburg, Germany, in 1901–02. In 1899 he joined the Sachsische Elektrizitatswerke, Poeschmann, Germany, working on design of electrical machinery. He entered the laboratory of the Land-und-See Kabelwerke, Cologne, Germany, in 1900, and in 1901 joined the Maschinenfabrik Eplingen, Stuttgart, Germany, as head of testing. In 1903 he came to the United States, and became designer for the Krantz Company, Brooklyn, N. Y., after which he was for a short time consulting engineer for the Hellmund and Collbohn Electric Company, New York, N. Y., before joining the William Stanley Company, Great Barrington, Mass., as designer. In 1905 he became designer for the Western Electric Company, Hawthorne, Ill., and in 1907 joined the Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa. From 1907 to 1909 he was engaged in design of induction motors, from 1909 to 1911 in general engineering, and from 1911 to 1917 was in charge of design of all a-c and d-c railway motors. He did miscellaneous consulting and development work from 1918 to 1921, was made engineering supervisor of development in 1922, and chief electrical engineer in 1926. Mr. Hellmund was himself awarded the Lamme Medal in 1929. He has been a member of the Institute's board of directors since 1939. He has been serving on the Lamme Medal committee since 1939, the executive committee and the Edison Medal committee since 1940 and the standards committee since 1930 (chairman 1938–40), and is now a member of the committee on application of electricity to therapeutics. He has been Institute representative on the electrical standards committee, American Standards Association, since 1938, standards council, ASA, since 1939, and the United States national committee of the International Electrotechnical Commission since 1938. He also formerly served on the AIEE planning and co-ordination committee.

N. E. Funk (A'07, F'34) vice-president in charge of engineering, Philadelphia Electric Company, Philadelphia, Pa., has been appointed chairman of the Institute's Edison Medal committee for 1941–42. He has served on the committee since 1938, and has also served on the following committees: power generation; transportation; legislation affecting the engineering profession; Lamme Medal (chairman 1936–38); code of principles of professional conduct; and finance. He was a member of the Institute's board of directors from 1934 to 1938. Mr. Funk was born at Bloomsburg, Pa., November 4, 1883, and received the degree of electrical engineer from Lehigh University in 1905. After taking the Westinghouse Electric and Manufacturing Company's apprentice shop course, he became subforeman

Bachrach

C. R. BEARDSLEY

L. R. MAPES

E. C. M. STAHL

Bachrach

R. E. HELLMUND

N. E. FUNK

P. L. ALGER

H. S. PHELPS

Bachrach

R. W. SORENSEN

for the New York Central Railroad Company, Berwick, Pa., and in 1906 became professor of electrical and experimental engineering at Georgia School of Technology, Atlanta, Ga. In 1907 he joined the Philadelphia Electric Company as assistant foreman of station construction, and was made assistant superintendent of operation in 1912. From 1912 to 1914 he was sales manager for the Sterling Switchboard Company, Camden, N. J., and in 1914 he returned to the Philadelphia Electric Company, serving first as secretary to the overhead line construction committee, National Electric Light Association, and then as combustion engineer for the company. He was made assistant to the operating engineer in 1915, and superintendent of the company's Schuylkill generating station in 1917. He became operating engineer for the company in 1918, assistant chief engineer in 1926, chief engineer, 1928, and, later the same year, assistant general manager. He has been vice-president in charge of engineering since 1929. He is also a member of The American Society of Mechanical Engineers and Franklin Institute.

P. L. Alger (A'17, F'30) staff assistant to vice-president in charge of design engineering, General Electric Company, Schenectady, N. Y., has been appointed chairman of the AIEE technical program committee and of the committee on award of Institute prizes for the year 1941–42. He was born January 27, 1894, in Washington, D. C., and received the degrees of bachelor of science from St. John's College, 1912, and Massachusetts Institute of Technology, 1915, and master of science from Union College, 1920. After a year as laboratory assistant at MIT, he entered the General Electric test course at Schenectady, in 1916, and later that year returned to MIT as research assistant. From 1917 to 1919 he served with the United States Army, and then entered the induction motor engineering department of the General Electric Company, Schenectady. In 1923 he was transferred to the a-c engineering department, and in 1927 was made assistant engineer of that department. He became staff assistant to the vice-president in charge of design engineering in 1929. He is the author of many technical articles. Mr. Alger was one of the United States delegates to the plenary meeting of the International Electrotechnical Commission at Torquay, England, in 1938. He has served on the technical program committee since 1939, and was a member of its predecessor, the committee on meetings and papers, from 1929 to 1932. He is a member of the committees on planning and co-ordination, standards (since 1932), and electrical machinery (chairman 1929–32), and has been a member of the Lamme Medal committee.

H. S. Phelps (A'21) engineer, special investigation and testing division, Philadelphia Electric Company, Philadelphia, Pa., has been appointed chairman of the Institute's publication committee for 1941–42. He has been a member of the committee since 1937, and is also a member of the committees on planning and co-ordination and award of Institute prizes, and has been AIEE representative on the American Co-ordinating Committee on Corrosion since 1938. He is a former member of the committees on power transmission and distribution and on communication. Mr. Phelps was born May 7, 1883, in Sanford, Fla., and attended Clarkson College of Technology. In 1906 he became an inspector in the engineering department of the New York Telephone Company, and from 1907 to 1909 was with the Denver Gas and Electric Company, Denver, Colo., as field engineer. During 1909 he was in charge of power plant operation for the Crystal River Marble Company, Marble, Colo. In 1910 he went to Lynn, Mass., and took the General Electric Company's student course, later doing design, testing, and special investigations for the company. In 1912 he entered the construction engineering department of the Mountain States Telephone and Telegraph Company, Denver, Colo., and from 1914 to 1917 was with the electrical division of the National Bureau of Standards, Washington, D. C., assisting in the preparation of data for the National Electrical Safety Code. From 1917 to 1920 he was electrical engineer with the Board of Railroad Commissioners of Iowa, Des Moines, Iowa. He has been with the Philadelphia Electric Company in various positions since 1920.

R. W. Sorensen (A'07, F'19) professor and head, department of electrical engineering, California Institute of Technology, Pasadena, Calif., has been appointed chairman of the AIEE committee on research for 1941–42. Doctor Sorensen was president of the Institute during 1940–41. He was a member of the research committee 1923–24 and 1927–30, and is now serving on the following committees: executive, Edison Medal (1938–42), and award of Institute prizes and as an Institute representative on the John Fritz Medal board of award. He is a member of the board of directors. He has formerly served on the committees on education, student Branches (chairman 1938–40), instruments and measurements, Lamme Medal, economic status of the engineer (chairman 1936–38), planning and co-ordination, executive (chairman 1940–41) Charles A. Coffin Fellowship and Research Fund, and membership, and as Institute representative on the American Engineering Council. Doctor Sorensen was born April 25, 1882, at Alta Vista, Kans., and received the degrees of bachelor of science in electrical engineering, 1905, and electrical engineer, 1928, and an honorary degree of doctor of science, 1938, from the University of Colorado. From 1905 to 1910 he was with the General Electric Company, Schenectady, N. Y., and Pittsfield, Mass., in the transformer departments, and in 1910 became associate professor of electrical engineering at Throop Polytechnic Institute, which later became California Institute of Technology. He was made professor and head of the department of electrical engineering in 1911. He is also a member of the Society for the Promotion of Engineering Education, Tau Beta Pi, and Sigma Xi, and is the author of many technical articles.

O. K. Marti (A'21, F'39) engineer in charge, rectifier equipment, Allis-Chalmers Manufacturing Company, Milwaukee, Wis., has been appointed consulting engineer of the company's rectifier division, to enable him to devote all his time to research and development work. Mr. Marti was design engineer for Brown, Boveri and Company, Baden, Switzerland, from 1916 to 1920. He came to the United States in 1920, and became research assistant at Cornell University, Ithaca, N. Y. He was made instructor in electrical engineering in 1923. In 1926 he joined the American Brown Boveri Electric Corporation, Camden, N. J., as consulting engineer, and was made chief engineer in 1927. When that company was taken over by the Allis-Chalmers company in 1931, he became engineer in charge of rectifier equipment for the latter. **H. Winograd** (A'26, M'39) electrical engineer, has been appointed engineer in charge of rectifier design. He was also associated with the American Brown Boveri Electric Corporation, joining it in 1925 as electrical engineer, and being put in charge of design of rectifier equipment in 1928. In 1931 he

G. A. KOSITZKY

O. E. BUCKLEY

I. M. STEIN

became electrical engineer for the Allis-Chalmers company, supervising design of electrical equipment. **J. F. Sellers** (A'34) electrical engineer, has been appointed engineer in charge of d-c design. He received the degree of bachelor of science in electrical engineering from Purdue University in 1923, and entered the Allis-Chalmers company the same year as a student apprentice. In 1934 he was transferred to the d-c engineering department, since which time he has been engaged in design of d-c machines. **G. W. Clothier** (A'36) electrical department, has been put in charge of transformer sales, a newly created department of the sales section of the transformer division of the company. From 1933 to 1936 Mr. Clothier was instructor in electrical engineering at the University of Washington, Seattle, Wash. He joined the Allis-Chalmers company in 1936 as a student engineer, and was transferred to the transformer division as electrical engineer about 1939. **R. O. Bell** (A'37) transformer division, has been placed in charge of feeder voltage regulator sales, another new department of the sales section of the transformer division. Mr. Bell joined the company in 1936 as student engineer, and was later transferred to the transformer division.

O. E. Buckley (M'19, F'29) president, Bell Telephone Laboratories, New York, N. Y., has been appointed chairman of the Institute's Charles LeGeyt Fortescue Fellowship committee for 1941–42. He has been a member of the committee since 1939, and has also served on the committees on electrophysics (chairman, 1929–31) and research. Doctor Buckley was born August 8, 1887, at Sloan, Iowa, and received the degrees of bachelor of science from Grinnell College, 1909, and doctor of philosophy, Cornell University, 1914. After a year as instructor in physics at Grinnell College, he went to Cornell University, Ithaca, N. Y., as assistant instructor in physics in 1910, becoming instructor in 1912. In 1914 he joined the Western Electric Company, Inc., New York, N. Y., as a member of the technical staff of the engineering department. After serving with the American Expeditionary Forces as a major in the United States Army Signal Corps during 1917–18, he returned to his former position with Western Electric Company, Inc. When the Bell Telephone Laboratories were incorporated in 1925, he was transferred to the technical staff of the Laboratories, and was made assistant director of research in 1928. He became director of research in 1933, and executive vice-president in 1937. He was appointed president of the Laboratories in 1940. He is the author of several technical articles, and owner of many patents. He is a member of the American Association for the Advancement of Science, the American Physical Society, Franklin Institute, Sigma Xi, and Phi Beta Kappa.

G. A. Kositzky (M'22, F'29) chief engineer, Ohio Bell Telephone Company, Cleveland, Ohio, has been appointed chairman of the Institute's committee on transfers for 1941–42. Born April 20, 1879, at Yankton, S. D., Mr. Kositzky received the degree of mechanical engineer in electrical engineering from Cornell University in 1905. He joined the New York and New Jersey Telephone Company, Brooklyn, N. Y., in 1905, and was made construction engineer in 1907. In 1910 he became division plant engineer for the Pacific Telephone and Telegraph Company, San Francisco, Calif., and in 1911 transferred to the Southwestern Bell Telephone Company serving as plant engineer and later as general plant superintendent at Kansas City, Mo., and then doing valuation work for the company in St. Louis, Mo. He became chief engineer of the Central Union Telephone Company, Chicago, Ill., in 1919, and has been chief engineer for the Ohio Bell Telephone Company since 1921. Mr. Kositzky has been a member of the committee on transfers since 1939, and has also served on the following committees: membership (chairman 1936–38), general power applications, communications (chairman 1929–31), and Edison Medal.

I. M. Stein (A'18, F'39) director of research, Leeds and Northrup Company, Philadelphia, Pa., has been appointed chairman of the Institute's committee on constitution and bylaws for 1941–42. He has been a member of the committee since 1938, and is now serving also on the following committees: Lamme Medal; planning and coordination (since 1938); publication (since 1934—chairman 1936–40); and as Institute representative on the council of the American Association for the Advancement of Science. He formerly has served on the committees on membership, Sections (chairman 1933–36), co-ordination of Institute activities, award of Institute prizes, technical program, Institute policy, and on several special committees. Mr. Stein was born March 30, 1894, in Long Branch, N. J. In 1911 he joined the New York Edison Company, New York, N. Y., as assistant in the meter department. He was transferred to the test department in 1912, and in 1914 was made supervisor of the standardizing laboratory. During 1918 he served as senior inspector in the United States Army Signal Corps, and in 1919 became affiliated with the Leeds and Northrup Company as sales engineer. In 1921 he was put in charge of general division sales, and in 1924 was made assistant sales manager. He was put in charge of development, engineering, production, publicity, and sales of combustion control apparatus in 1927, and later made director of research. He is also a member of the American Physical Society, American Chemical Society, American Electrochemical Society, Association of Iron and Steel Engineers, Franklin Institute, American Society of Mechanical Engineers, American Society for Testing Materials, and the Illuminating Engineering Society. He is the author of many technical articles.

C. G. Koppitz (M'21) chief engineer, Railway and Industrial Engineering Company, Greensburg, Pa., has been appointed vice-president and consulting engineer for the company. Mr. Koppitz was born January 10, 1878, in San Francisco, Calif., and attended the Massachusetts Institute of Technology. From 1900 to 1902 he was engaged in construction and operation of various power houses and substations in Paris for several French companies, and in 1902 went to London as sales engineer for the British Westinghouse Electric and Manufacturing Company, later being transferred to Birmingham. He returned to the United States in 1904 and engaged in consulting engineering work in San Francisco, Calif. In 1908 he became electrical engineer for the Youngstown, Ohio, Consolidated Gas and Electric Company and the Mahoning and Shenango Railway and Light Company. From 1911 to 1914 he engaged in private research, and in design of power houses for the West Penn Power Company, and in 1914 joined the Railway and Industrial Engineering Company as chief engineer.

Philip Sporn (A'20, F'30) vice-president in charge of engineering, American Gas and Electric Service Corporation, New York, N. Y., and **Constantine Bary** (A'25) rate research engineer, rate and standard practice department, the Philadelphia Electric Company, Philadelphia, Pa., have been appointed to the consulting board of the newly created defense power planning agency of the Office of Production Management. **J. C. Parker** (A'04, F'12) vice-president, Consolidated Edison Company of New York, Inc., New York, N. Y., has been appointed to the staff of the OPM power division to handle priorities.

W. H. Harrison (A'20, F'31) who has been in charge of the shipbuilding, construction, and supplies branch of the production division of the Office of Production Management, has been made chief of the production division in the current reorganization of national defense agencies. Mr. Harrison went to Washington in 1940 from his position as vice-president and chief engineer of the American Telephone and Telegraph Co., New York, N. Y., and has been given in-

creasingly broad responsibilities in the successive shifts in the defense setup. He is a past president of the AIEE.

J. E. Hobson (A'36) central station engineer, Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa., has been appointed director of the electrical engineering department, Illinois Institute of Technology, Chicago, Ill. A biographical sketch of Doctor Hobson appeared in the January 1941 issue, page 42, in connection with his being chosen "outstanding young electrical engineer for 1940" by Eta Kappa Nu.

G. S. Diehl (A'17) assistant to superintendent of operation, Pennsylvania Water and Power Company, Baltimore, Md., has been elected chairman of the accident prevention committee of the Edison Electric Institute for 1941–42. **E. V. Sayles** (A'23, F'38) electrical engineer, Commonwealth and Southern Corporation, Jackson, Mich., has been elected chairman of the transmission and distribution committee of the EEI.

Harold Torgersen (A'31, M'39) of the department of electrical engineering, New York University college of engineering, New York, N. Y., and a lieutenant in the United States Naval Reserve, has been assigned to a teaching position at the United States Naval Academy, Annapolis, Md. He will continue to act as an advisor in high-voltage research at the University.

J. C. Clark (A'09, M'21) professor of electrical engineering, University of Arizona, Tucson, has been appointed electrical engineer on the staff of the engineering experiment station recently organized by the University. **O. H. Polk** (A'35) associate professor of electrical engineering, has been appointed associate electrical engineer for the experiment station.

L. M. Klauber (A'11, F'23) vice-president and general manager of the San Diego Consolidated Gas and Electric Company, San Diego, Calif., has been awarded the honorary degree of doctor of laws by the University of California.

W. F. Grimes (A'19, M'27) recently returned to active duty as radio material officer of the Eleventh Naval District, San Diego, Calif., has been promoted to the rank of Commander in the United States Naval Reserve.

W. H. Colburn (A'20, M'26) commercial engineer, the Boston Edison Company, Boston, Mass., has been elected chairman of the Power Engineers Association of New England.

H. C. Rentschler (M'40) director of lamp research, Westinghouse Electric and Manufacturing Company, Bloomfield, N. J., has been awarded an honorary degree of doctor of science by Princeton University.

Obituary • • •

Ernst Julius Berg (A'94, M'02, F'13) retired head of the electrical-engineering department, Union College, Schenectady, N. Y., died September 9, 1941. Born January 9, 1871, at Oestersund, Sweden, he received the degrees of mechanical engineer from the Royal Polytecknicum, Stockholm, 1892, and doctor of science from Union College, 1910. He came to the United States in 1892 and became electrical engineer for the Thomson-Houston Company, Lynn, Mass., and later was transferred to the General Electric Company, Schenectady, N. Y., where he served as assistant to Doctor Charles P. Steinmetz. In 1904 he was made consulting engineer for the company, and was consulting professor of electrical engineering for Union College, from 1907 to 1909. In 1910 he joined the faculty of the University of Illinois, Urbana, Ill., as professor of electrical engineering, and returned to fill the same position at Union College in 1913. He was made head of the electrical engineering department there in 1932, and retired in June 1941. He was the author of "Electrical Energy" (1908), "Advanced Course in Electrical Engineering" (1916), "Heaviside's Operational Calculus" (1929), and co-author with W. L. Upson of "First Course in Electrical Engineering" (1916). He had contributed many articles to the technical press. He served the Institute on several committees. He was also a member of Tau Beta Pi, Eta Kappa Nu, and Sigma Xi.

Leslie Nathaniel Crichton (A'08, M'21) relay design engineer, Westinghouse Electric and Manufacturing Company, Newark, N. J., died September 6, 1941. Mr. Crichton was born December 29, 1885, at Parsons, Kans., and received the degree of bachelor of science in electrical engineering from the University of Missouri in 1906. In 1906 he joined the Telluride Power Company, Salt Lake City, Utah, as apprentice and station operator, becoming draftsman on hydroelectric powerhouse design in 1907 and assistant in the testing and standard laboratories in 1908. From 1909 to 1911 he was in charge of the standard and testing laboratories. In 1912 he became designing engineer for the Utah Power and Light Company, successor to the Telluride Power Company. He became affiliated with the Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa., in 1915, as designer of protective relays. During 1918–19 he served as an engineer officer in the United States Navy, and in 1919 returned to Westinghouse, working in the research department. He was made relay design engineer about 1920, and was transferred to the meter division at Newark about 1927. He was the author of a number of inventions, and had served several times on the Institute committee on protective devices.

Emil Leonarz (A'08, M'08, F'13) director general, Compagnia Fundidora de Fierro y Acero de Monterrey S. A., Monterrey, Mexico, died July 24, 1941. Born June 3, 1873, in Baumholder, Germany, Mr. Leonarz studied electrical engineering in Technikum Mittweida and at the Technical University, Darmstadt, Germany. In 1896 he joined Schuckert and Company (later, Siemens-Schuckert and Company) Berlin and Nuremberg, Germany, working on power plant design and erection, and later on technical calculations for alternating-current and polyphase generators. He went to Mexico in 1905 as chief engineer of distribution for the Mexican Light and Power Company, Mexico City. From 1909 to 1911 he was consulting engineer for the company, and in 1911 became manager of the Monterrey Railway, Light, and Power Company. From 1915 to about 1918 he practiced consulting engineering, and then became professor of electrical engineering at the Practical School of Mechanical and Electrical Engineering, Mexico City. In 1922 he became assistant manager of the Compagnia Fundidora de Fierro y Acero de Monterrey S. A., later becoming managing director. He retired from that position in 1940, but continued to serve in a consulting capacity and as a member of the board of directors.

Frederick Howard Babcock (A'28) manager of the New York Central-Station division, General Electric Company, New York, N. Y., died August 31, 1941. Mr. Babcock was born March 4, 1887, at Watertown, N. Y., and graduated from the United States Naval Academy in 1908. After three years in the engineering department of the United States Navy, he entered the test course of the General Electric Company, at Schenectady, N. Y., in 1911. In 1912 he was transferred to the lighting engineering department of the company, and in 1917 entered the central-station engineering department. During 1917–18 he served as a lieutenant in the United States Navy, and at the end of the war returned to his former position with the General Electric Company. In 1927 he was transferred to the New York office of the company as assistant to the vice-president, and in 1940 was made manager of the New York central-station division. Mr. Babcock was a director of the Edison General Electric Appliance Company, and of the Locke Insulator Corporation.

Frederick Dammett Sampson (A'96, M'97) superintendent of distribution, Duke Power Company, Charlotte, N. C., died August 24, 1941. Mr. Sampson was born February 11, 1867, at Gravesend, Kent, England and was educated there. In 1883 he came to the United States, and in 1897 joined the Northwest Thomson-Houston Company, doing installation work for that company and for the Northwest General Electric Company until 1894. He then became electrician for the Lake Roland Elevated Railway, Baltimore, Md., and in 1895 was appointed manager of plant for the Charlotte Electric Railway, Light and Power Company, Charlotte, N. C. In 1904 he became superintendent of construction and distribution for the Catawba Power Company, Charlotte, N. C., continuing in that position with its successor, the Southern Power Company. He became superintendent of distribution for the Duke Power Company, successor to the Southern Power Company, about 1928.

John M. Costello (A'27) vice-president, Central New York Power Corporation, Syracuse, N. Y., died August 15, 1941. Mr. Costello was born October 6, 1891, in

Clyde, N. Y. In 1911 he joined the Niagara, Lockport, and Ontario Power Company, a subsidiary of the Niagara Hudson Power Corporation, and when the Livingston Niagara Power Company, Syracuse, N. Y., was merged with the Niagara, Lockport, and Ontario Power Company in 1925 he was made division superintendent, general manager, and district manager of the eastern division of the former company. About 1928 he became executive manager of the Niagara, Lockport, and Ontario Power Company, and about 1930 became vice-president and general manager of the Syracuse Lighting Company, Inc., another subsidiary of the Niagara Hudson Power Corporation. He became vice-president of the Central New York Power Corporation, also a Niagara Hudson subsidiary, about 1937.

Membership • •

Recommended for Transfer

The board of examiners, at its meeting on September 11, 1941, recommended the following members for transfer to the grade of membership indicated. Any objection to these transfers should be filed at once with the national secretary.

To Grade of Fellow

Albert, A. L., professor of communication engineering, Oregon State College, Corvallis.

North, J. R., assistant electrical engineer, Commonwealth and Southern Corporation, Jackson, Mich.

Powel, C. A., manager, headquarters engineering departments, Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa.

Reagan, M. E., section engineer, Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa.

4 to Grade of Fellow

To Grade of Member

Ager, R. W., associate professor of electrical engineering, Cornell University, Ithaca, N. Y.

Alfriend, J. V., Jr., engineer, Federal Power Commission, Washington, D. C.

Alspaugh, R. M., associate electrical engineer, Tennessee Valley Authority, Knoxville, Tenn.

Atkinson, L. G., Jr., section manager, Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa.

Bergvall, R. C., assistant to vice-president, Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa.

Brown, K. R., consulting engineer, Des Moines, Iowa.

Byers, R. M., assistant to electrical engineer, Consolidated Gas Electric Light and Power Company, Baltimore, Md.

Dalger, G. P., director of laboratories, The Hoover Company, North Canton, Ohio.

Daykin, H. R., sales manager, The Bostwick Braun Company, Toledo, Ohio.

Erikson, R. A., engineer, Commonwealth Edison Company, Chicago, Ill.

French, C. J., associate electrical engineer, Bonneville Power Administration, Portland, Ore.

Glaze, H. C., Jr., electrical engineer, General Electric Company, Portland, Ore.

Grettum, L. A., vice-president and general manager, Eastern Oregon Light and Power Company, Baker, Ore.

Halliday, U. N., sales engineer, Pacific Electric Manufacturing Company, Denver, Colo.

Herbold, C. F., manager, industrial relations department, Westinghouse Electric and Manufacturing Company, Lima, Ohio.

Hobson, J. E., director, school of electrical engineering, Illinois Institute of Technology, Chicago, Ill.

Hynes, W. F., northwestern district sales manager, General Electric Company, Portland, Ore.

Keto, A. I., design engineer, transformers, Westinghouse Electric and Manufacturing Company, Sharon, Pa.

Kimberly, R. E., consulting engineer, and professor of electrical engineering, Ohio State University, Columbus, Ohio.

Kinney, E. E., assistant professor of electrical engineering, Michigan State College, East Lansing, Mich.

LaPoe, A. E., central district engineer and service manager, Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa.

Lindblad, assistant chief, bureau of tests and inspection, Pacific Gas and Electric Company, Emeryville, Calif.

Lipscomb, E. W., field engineer, Western Union Telegraph Company, Dallas, Texas.

Martsolf, C. M., engineer of plant extension, Bell Telephone Company of Pa., Pittsburgh, Pa.

Meihoff, A. D., distribution engineer, Northwestern Electric Company, Portland, Ore.

Menmuir, J. B., Captain, U. S. Army, Bear Field, Forty Wayne, Ind.

Mitchell, C. F., service conversion and regulation engineer, Commonwealth Edison Company, Chicago, Ill.

Moreland, H. D., district manager, X-ray division, Westinghouse Electric and Manufacturing Company, Portland, Ore.

Opsahl, A. M., design engineer, lightning arresters, Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa.

Packard, L. E., engineering representative in New York, General Radio Company, New York, N. Y.

Paige, E. R., supervisor, Buffalo Niagara Electric Corporation, Buffalo, N. Y.

Proctor, J. A. M., chief maintenance electrician, Demerara Bauxite Company, Mackenzie City, British Guiana, S. A.

Riker, C. B., supervisor, extension training, Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa.

Sidway, C. L., electrical machine designer, Department of Water and Power, City of Los Angeles, Calif.

Stansel, R. R., member of technical staff, Bell Telephone Laboratories, New York.

Stresmer, A. G., vice-president, general manager, Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa.

Vogel, F. J., consulting engineer, Westinghouse Electric and Manufacturing Company, Sharon, Pa.

Willis, B. S., assistant professor of electrical engineering, Iowa State College, Ames, Iowa.

38 to Grade of Member

Applications for Election

Applications have been received at headquarters from the following candidates for election to membership in the Institute. Names of applicants in the United States and Canada are arranged by geodetic Districts. If the applicant has applied for direct admission to a grade higher than Associate, the grade follows immediately after the name. Any member objecting to the election of any of these candidates should so inform the national secretary before October 31, 1941, or December 31, 1941 if the applicant resides outside of the United States or Canada.

United States and Canada

1. NORTH EASTERN

Dolan, L. E., United States Navy, Bureau Yards and Docks, Newport, R. I.

Pugsley, R. F., United States Navy, Electric Boat Company, Groton, Conn.

Stocking, R. H., General Electric Company, Schenectady, N. Y.

Thelen, J. L., General Electric Company, Lynn, Mass.

Wolf, E. M., Rome Cable Corporation, Rome, N. Y.

2. MIDDLE EASTERN

Brancke, C. A., General Electric Company, Erie, Pa.

Hoffman, W., B. F. Goodrich Company, Akron, Ohio.

Meyers, G. N., Edward G. Budd Manufacturing Company, Philadelphia, Pa.

Moreton, S., General Electric Company, Philadelphia, Pa.

3. NEW YORK CITY

Akaman, L., 30 Church Street, New York, N. Y.

Anderson, J. B. (Member), Theodore Audel and Company, New York, N. Y.

Cummings, C. S. (Member), Western Union Telegraph Company, New York, N. Y.

Davenport, C., Jr. (Member), Bell Telephone Laboratories, Inc., New York, N. Y.

Davidson, J. M., Presbyterian Hospital, New York, N. Y.

Dellis, P. L. (Member), Amitas Limited, New York, N. Y.

Eberhardt, E. T., Subox Incorporated, North Arlington, N. J.

Hellegers, J. (Member), Syska and Hennessy, Consulting Engineers, New York, N. Y.

Jacobs, M. C., Kaplan Electric Corporation, New York, N. Y.

Podchaski, P. P. (Member), Polish Information Center, New York, N. Y.

Walechka, C. A., General Cable Corporation, Bayonne, N. J.

4. SOUTHERN

Armentrout, L. S., City Electric Department, Harrisonburg, Va.

5. GREAT LAKES

Dudrey, H. E., Electrical Contractor, Moorhead, Minn.

Johnson, R. P., Central Illinois Light Company, Peoria, Ill.

Limpel, E. J., A. O. Smith Corporation, Milwaukee, Wis.

Sherwood, W. W. (Associate re-election), Sangamo Electric Company, Springfield, Ill.

Wilson, A. P., Bendix Products Division, South Bend, Ind.

6. NORTH CENTRAL

Setter, J. A. (Associate re-election), General Electric Company, Denver, Colo.

7. SOUTH WEST

Hantla, O. R., Kansas Gas and Electric Company, Wichita, Kans.

Skinner, H. A., Southwestern Bell Telephone Company, Tulsa, Okla.

Sloan, C. A., Kansas City Power and Light Company, Kansas City, Mo.

8. PACIFIC

Berberich, F. J., Jr., Douglas Aircraft Company, Inc., Santa Monica, Calif.

Bussi, J. E., Pacific Electric Manufacturing Company, San Francisco, Calif.

Dowd, M. J. (Member), Imperial Irrigation District, Imperial, Calif.

Sexton, C. R., H. B. Held, 420 Market Street, San Francisco, Calif.

Willson, W. G., Westinghouse Electric and Manufacturing Company, Phoenix, Ariz.

9. NORTH WEST

Emory, G. H. (Member), Austin Company, United States Naval Air Station, Sand Point, Seattle, Wash.

Gochnauer, R. L., United States Bureau of Reclamation, Coulee Dam, Wash.

10. CANADA

Humpage, M. E., Ferranti Electric, Ltd., Mount Dennis, Toronto, Ont.

McDiarmid, J. F., Hamilton Hydro-Electric System, Hamilton, Ont.

Speight, J. W., Hydro-Electric Power Commission of Ontario, Toronto, Ont.

Webb, E. J., Ferranti Electric, Ltd., Mount Dennis, Toronto, Ont.

Total, United States and Canada, 41

Elsewhere

Aaron, A., National Tobacco Company of India, Ltd., Guntur, India.

Freeman, T. S. A., Heap and Partners, Ltd., St. Johns, Newfoundland.

Jeffery, L. G. (Member), H. M. Fleet Air Arm, Naval Base, Singapore, Straits Settlements.

Yao, Y. Y., Wha Tung Electrical and General Engineering Works, Shanghai, China.

Total, elsewhere, 4

Addresses Wanted

A list of members whose mail has been returned by the postal authorities is given below, with the addresses as they now appear on the Institute record. Any member knowing of corrections to these addresses will kindly communicate them at once to the office of the secretary at 33 West 39th St., New York, N. Y.

Accioly, Pompeu Barbosa, Caixa Postal 571, Rio de Janeiro, Brazil, S. A.

Anderson, Axel W., Jr., 647 W. Sheridan Road, Chicago, Ill.

Browning, Robert Lee, Jr., c/o Continental Oil Co., Conroe, Texas.

Butler, N. O., Route 1, Moore, Okla.

Butler, Oliver D., 1355 E. 47th Place, Chicago, Ill.

Chase, Charles W., 900 Traction Terminal Bldg., Indianapolis, Ind.

Clinchard, W. C., Jr., Fajardo Sugar Co., Fajardo, P. R.

Cohen, LeRoy Daniel, 770 Meridian St., Florence, Ala.

Daily, Charles S., Jr., 1723 Rye St., N. W., Washington, D. C.

Dennis, Roman, Jr., 360 Amherst St., Buffalo, N. Y.

Dively, William L., c/o Ford Hotel, Buffalo, N. Y.

Dusenbury, Charles, 6744 Penna Ave., Pittsburgh, Pa.

Gould, John P., 2707 S. 59th Court, Cicero, Ill.

Griffin, B. E., 2619–25 Santa Fe Ave., Los Angeles, Calif.

Hickey, Frank W., Jr., 750 Taylor St., San Francisco, Calif.

Hurd, Clinton T., Box 178, Seattle, Wash.

Huse, Raymond A., 60 Prospect Ave., Hackensack, N. J.

Romero, Robert F., 3200—13th St., N. W., Washington, D. C.

Schwarz, Donald William, 115 Lincoln Ave., Endicott, N. Y.

Smith, Clement E., 816 Leland Ave., South Bend, Ind.

Swan, Harry C., 586 Shoop Ave., Dayton, Ohio.

Thompson, Haddon, Stordèn, Minn.

Waddell, Robert A., 510 Hill Ave., Wilkinsburg, Pa.

Wood, Frank Preuit, Dallas Power and Light Co., Dallas, Texas.

24 Addresses Wanted

Of Current Interest

National Defense

Shortages of Minerals and Metals to Become More Acute

At a recent gathering of trade-journal editors in New York, N. Y., Robert E. McConnell, chief of the conservation unit, production division, Office of Production Management, Washington, D. C., outlined the situation regarding present and expected shortages of "critical" minerals and metals now being used in such large quantities in the National Defense program. The essential substance of Mr. McConnell's remarks follows.

Whatever we may have thought up until now, whatever has been said up until now, the plain fact of the present situation is that the Defense program plus Lend-Lease is now of such magnitude that there is an immediate shortage of practically all minerals and metals. This situation is not going to get any better and prudence plus the experience of last year can lead to no other conclusion than that the situation will get worse. Therefore, the immediate job and one of the biggest jobs in the whole program is to get along as best we can with less, and to make what we have go as far as it possibly can. In practical terms, this means conservation, substitution, reclamation, and simplification of design. The major part of this job must be done within industry, in private factories, by individual engineers.

ALUMINUM

The present rate of production is approximately 600,000,000 pounds a year. This has been stepped up from peace-time production of 300,000,000 pounds. Within the next 12 months it is expected the rate of production will reach 900,000,000 pounds per year and arrangements have been made to bring 200,000,000 pounds from Canada. During the third six months additional plants will bring the supply to 1,600,000,000 pounds of virgin aluminum per year.

After this program is in operation, it is estimated that about 500,000,000 pounds of scrap per year will be produced which will also be available for defense requirements. Scrap aluminum is mostly alloy, from which it is very difficult to separate the pure aluminum. This program (of 1,600,000,000 pounds per year) is going to create a power problem, and there may have to be some curtailment in large areas in the country of the power consumed for nonessential purposes.

There is also a question of the domestic high-grade bauxite supply, which at present is estimated to be sufficient to last about three years. Imports from the northern coast of South America will be continued, but ships are badly needed in the Atlantic. Surveys looking toward the use of lower-grade materials are being made.

COPPER

Current production in the United States is about 1,100,000 tons. At present imports of 400,000 tons per year are coming from South America. The Canadian production is going to England. The Rhodesia production is also going to England. Some 170,000 tons per year is being sent from this country to England. About 525,000 tons per year is required for brass, mostly for shell cases. Some 200,000 tons are required for direct electrical defense, some 300,000 for indirect electrical defense requirements, and 100,000 tons for degaussing cable. This leaves some 300,000 tons for nonessential uses. Normal peace-time requirements of nondefense industries are at the rate of 850,000 to 900,000 tons of copper a year if available. There is some prospect of increasing copper production some 10 or 15 per cent. As long as this shortage exists, we are not going to have enough copper for nonessential industries. Conservation of all uses of copper should be undertaken immediately.

ZINC

Current rate of zinc production is approximately 950,000 tons a year. Total Army and Navy requirements are about 550,000 tons per year, and it is probable that this demand will be increased. This leaves about 400,000 tons per year of zinc to fill estimated civilian nondefense requirements of 750,000 tons. The zinc shortage has been reduced by increased facilities and by conservation. We believe that 100,000 tons of zinc a year have been saved by conservation or substitution in the past few months. A large part of it has been in the automobile industry, and a reduction has been made in the amount of zinc used in galvanizing. There is no way of enforcing such conservation requests by law, but despite this fact the results to date have been exceedingly gratifying.

STRATEGICAL IMPORTED MATERIALS FROM THE FAR EAST

Manganese, chrome, and rubber comprise about 70 per cent of the total tonnage of strategic imports from the Far East. Current manganese consumption is about 1,400,000 tons a year. Chrome ore is required at about 800,000 to 850,000 tons a year. Rubber (including stock-pile requirements) is expected to be brought in at a rate of 1,000,000 tons a year. By reason of cooperative action of industry, rubber consumption has been cut from 800,000 to 600,000 tons per year, of which the defense requirements are between 85,000 and 100,000 tons per year. Truck production may be increased from 800,000 units to 1,200,000 units per year, and the burden of the necessary decrease in rubber consumption will, therefore, fall on passenger-car production. Of the total strategic imports from the Far East, the automobile industry has been taking nearly 30 per cent. This fact, and the shortage of all metals, are the controlling reasons for the cut in automobile production.

TIN

Consumption of tin is at the rate of 100,000 tons a year. Because reserves have been built up, the statistical situation is good and there is more tin relative to our immediate needs in this country than there has been previously. Stocks are sufficient for some 15 months' consumption. However, owing to the uncertainties in the Far East, conservation has affected tin consumption by about 10 to 15 per cent. The canning industry uses 50 per cent of total tin. By reducing tin gauge in cans and using substitute materials, it is estimated that a saving of 10,000 tons of tin a year has been effected. About 1,000 tons has been saved in the collapsible tube industry. We may at a later date require the tin can industry to make further reductions. The tin conservation to date has been effected by requesting the industry to co-operate and has been accomplished without disturbing labor or facilities.

A three-year supply has been the stock-pile objective for all strategic materials. Present stocks will not exceed 15 to 18 months' supply. Rubber imports were increased from 750,000 to 1,000,000 tons a month beginning in July. Importations at a rate of 1,000,000 tons a year and consumption 600,000 tons will add 600,000 tons a year to the rubber stock pile. Some 50,000 tons of artificial-rubber plant capacity is now under construction. There are three or four different types of plants under way and they should be finished in 14 or 16 months.

STEEL

Steel is short. Engineers who are designing steel equipment can perform an extremely valuable function by practicing conservation. This year we will produce about 87,000,000 tons of steel. If we increase that production by 10,000,000 tons a year it will be necessary to build up all departments of the steel industry. Such additional steel capacity will require construction of 40 additional 10,000-ton lake ore boats. Ways will have to be put up before these boats can be built. New facilities will require much time and materials.

I am hopeful that the engineers will help to establish some co-operative exchange of steel conservation ideas in an effort to reduce consumption of steel, without retarding defense programs and without increasing cost unduly. In 1918, steel production was raised to 48,000,000 tons. Then there were 2,000,000 men under arms in Europe and 2,000,000 in training here. We now have 1,500,000 in the armed forces and a steel production rate of 87,000,000 tons per year. I can't overemphasize the importance of the steel-conservation problem. Many accomplishments can be made by the engineers.

A campaign should be initiated to modify building codes. Figures indicate that a

saving of 50 per cent of metals could be effected through the adoption of the Federal Plumbers' Manual in place of the 1,600 existing municipal codes. The present codes are padded with material, and labor and any changes would be resisted.

Nickel is produced in Canada at a rate of about 21,000,000 pounds per month. Of that amount England is taking 6,000,000 pounds a month and defense requirements here total about 13,000,000 pounds. This leaves between 1,000,000 and 2,000,000 pounds for nondefense industry. The civilian demand is probably about 8,000,000 or 9,000,000 judging by industrial activity.

It is unlikely that nickel will be taken off the priorities list. It takes a long time to develop new mines; the present supply must be conserved.

Molybdenum output is being increased. Molybdenum is "tight," but it is one of the lesser headaches. Reserves are large.

There is a very serious shortage of scrap iron. We have plans under way to try to increase the supply. It will be difficult, with this price ceiling, to obtain quantities of scrap iron from remote areas. There is a large amount of scrap iron in old motor cars, perhaps 4,000,000 or 5,000,000 tons in cars in wreckers' yards. A plan for securing this metal has been tested in Ohio and several plans are being studied.

The aluminum drive which this Section initiated and carried on has thoroughly demonstrated the willingness and desire on the part of the public to help the National Defense program. People want to participate. They want to do something constructive. There are four shortage problems that have affected the public so far—the aluminum drive, the oil shortage in the Northeast, the power shortage in the Southeast, and now the silk shortage.

In the future, Government agencies may properly inaugurate some method to give preference to those bidders on Government contracts who submit bids and designs which embody conservation of those critical and strategic materials in which serious shortages exist. In many cases it is not entirely a question of cost, if by conservation we can assure better usage of strategic materials. Design engineers should post over their drafting boards a list of all the defense materials in which serious shortages exist, as a reminder that they can help the national defense program by using such materials sparingly.

SIMPLIFICATION IS NOT STANDARDIZATION

Simplification, as it is now conceived, contemplates a reduction in the number of models and number of designs. For example, many types of plows, axes, collapsible tubes, bicycles, and many other products could be eliminated. The bicycle manufacturers make an average of 35 models each. They may be asked to reduce the total number of models to six or eight each, to take off all metallic finishes and to use reclaimed rubber instead of raw rubber. If the Government requests that these changes be made by all bicycle manufacturers, there would be no competitive advantage or disadvantage because it seems assured from past experience that all manufacturers would comply if requested to do so.

A price ceiling has been placed on most raw materials and many finished products. Some control of this character is essential to avoid runaway markets, competitive bidding, high-cost Government work and subsequent inflation. However, the control is artificial and the law of supply and demand is therefore "under wraps." Under artificial price restrictions conservation economics in usage of materials becomes of great importance and is necessary to take the place of the normal restrictions that would be brought into play if high prices prevailed.

Industry Curtails Use of "Critical" Materials

Because the requirements of the National Defense program have resulted in severe shortages of many materials, the manufacturers of products not essential to defense have found it necessary to alter production programs, seek substitute materials, or cease the manufacture of some items. Designs of many products are being altered to use materials in smaller quantities and to better advantage, and to utilize substitute materials in many instances.

Many products, however, cannot be manufactured satisfactorily with substitute materials, and therefore the manufacture of some products must be drastically curtailed and may have to be suspended. This situation is being felt acutely by many smaller industries manufacturing only a single product, but more and more subcontracting to these smaller plants of primary defense contracts is being urged so as to lessen the hardships of these industries.

Typifying what is happening in the automotive field, the reductions made by General Motors are indicated in the accompanying tabulation. Design changes have reduced the amount of aluminum, nickel, magnesium, zinc, and tungsten required per car, at the expense of increases in the quantities of chromium, copper, lead, and tin.

In the Bell Telephone System, substitutions of other materials for "critical" materials is expected to divert for use in defense work nearly 1,700,000 pounds of aluminum, almost a third of a million pounds of nickel, more than 3,000,000 pounds of zinc, and 8,300 pounds of magnesium. The substitution of steel for aluminum in the finger wheels of dial phones is expected to save 65 tons of aluminum annually. In many instances, metal die castings will be replaced by plastics. The System also is making greater efforts to salvage scrap material.

In the electrical-appliance field, manufacturers face a necessary curtailment in production, but beyond that efforts are now being made to standardize these products so as to reduce all unnecessary variety in sizes and styles and to conserve production facilities. The American Standards Association has announced that work already has begun on standardization of electric refrigerators, domestic washing machines, and flat irons. On account of the urgency of the situation, ASA has been requested to develop these standards by the short-cut emergency procedure that is being used in the case of some of the standards needed in defense production. It is expected that these standards will specify such items as number of sizes, method of rating, minimum performance standards, and minimum construction standards.

"Critical" Material Requirements for 1941 and 1942 General Motors Passenger Cars

Material	Pounds Per Car Average 1941	Pounds Per Car Average 1942	Design Saving (Per Cent)	Pounds Saved, Including Volume Reduction
Aluminum	7.6	1.8	76.	14,148,000
Nickel	3.6	1.7	53.	5,899,000
Magnesium	0.047	0.005	89.	92,300
Zinc	53.8	18.9	64.	92,027,000
Chromium	4.5	4.6	— 2.	4,957,000
Copper	51.9	55.1	— 6.	55,603,000
Lead	32.5	34.4	— 6.	34,916,000
Tin	2.7	2.8	— 4.	2,955,000
Tungsten	0.0075	0.0074	1.	9,000
1941 Production Volume				2,082,422 Cars
1942 Production Allotment (Tentative)				950,956 Cars

Accident-Prevention Campaign Organized to Aid Defense

The National Safety Council has been asked by the President of the United States to head an intensified nation-wide campaign against accidents, which, by taking toll of life and property, constitute a serious hindrance to the defense effort. Enlisting the co-operation of various national organizations, including the AIEE, the Council opened the campaign with an Emergency Safety Conference in New York, N. Y., September 9, 1941. The conference was attended by some 140 persons, representing about 100 national organizations.

For efficiency in organizing its program, the conference was divided into five committees, which, with their chairmen, are:

Industry, R. T. Sloensten, vice-president of the National Safety Council

Transportation, T. H. MacDonald, commissioner, United States Public Roads Administration

Homes and Farms, George Adler, Good Housekeeping Institute

Child Safety, Willard B. Givens, American Association of School Administrators

Public Information, Carl L. Smith, managing director, Greater Cleveland Safety Council

The industrial safety committee, the first of the committees to issue a report, made the following recommendations:

"1. That executives of every industrial organization recognize the prime importance of aggressive management leadership in accident prevention. This leadership must be given wholeheartedly and continuously if safety is to receive adequate attention during the rush of defense production.

"2. That organizations of employees continuously emphasize to their members the possible serious consequences of accidents, both financial and otherwise, and that they co-operate with industrial management in formulating and applying sound and reasonable procedures for safeguarding employees.

"3. That managements recognize the high cost of accidents, both in time and money, and the consequent importance of judicious expenditures for correcting accident hazards, safeguarding equipment, and educating employees. Money spent on safety is really an investment in economy of operation.

"4. That management take positive steps to meet the special difficulties now encountered in maintaining a safe working place. Overcrowding and con-

fusion resulting from expanded operations are a constant accident threat.

"5. That industry recognize the key position of the supervisor and foreman in training workers for safety and in maintaining safe standards of operation. In these times of industrial stress, it should be realized that demands on supervisors to meet production schedules must not be so extreme as to make safe operation impossible.

"6. That both employer and employee refuse to accept the idea that the defense program in industry requires chance-taking. Plants where there is a disposition to speed up operations regardless of possible serious losses of men and material through accidents are not in line with the safety principles laid down in the President's proclamation.

"7. That injuries to workmen in off-the-job accidents be recognized as losses to industry of equal seriousness to injuries occurring on the job. The defense program is retarded no less when a skilled mechanic is disabled in a home accident or a traffic accident than when he is injured at work."

The committee also recommended that the principles and program suggested in its report "be placed immediately in the hands of industrial management and industrial employees, through such means as: publications, convention addresses, safety committees, letters, personal safety service, pamphlets, posters, and other means."

OPM Has Advisory Program for Training Within Industry

The Office of Production Management has set up a country-wide organization to assist defense manufacturers in meeting the increasing need for skilled workers and supervisors by training within industry. The organization renders advisory assistance to defense industries in inaugurating programs which they carry on within their own plants at their own expense. In no way compulsory, the service is supplied only at the request of management.

Requests for assistance received by the "Training Within Industry" program show that the problem of providing needed skills falls into three divisions:

1. **Taking stock of present skills.** Each plant should make its own inventory of both unemployed and those employed below their greatest usefulness, in addition to making use of similar information being gathered by national and local agencies.

2. *Training outside of industry.* Pre-employment instruction and supplementary instruction, while being provided by public and private vocational schools and engineering colleges, requires the fullest co-operation of industry in order that those who complete such training will be acceptable for employment, and that the numbers trained are not greatly in excess of the needs of the industries concerned. The National Youth Administration, Work Projects Administration, and Civilian Conservation Corps also offer opportunities for pre-employment work experience which can be related to defense industry needs.

3. *Training within industry.* Industry's own training responsibilities, with which this program is particularly concerned, include upgrading of all classes of personnel as their experience and abilities warrant, through planned job progression, job rotation, and intensive supplementary instruction both on and off the job. The experience of the Training Within Industry organization shows that such training will be aimed at the development of three principal types of skill: production specialists, skilled mechanics, and supervisors, including technical and management assistants.

The organization's assistance to industries covers help in analyzing training needs and in setting up a plant training program which meets those needs; serving as a clearing house through which experience of employers in meeting the problem is made available, and as a liaison organization between industry and the tax-supported agencies providing pre-employment instruction. The Training Within Industry branch of OPM's labor division has 22 district offices, each headed by a district representative borrowed from industry, and including on its staff two advisers representing management, two representing labor, and several consultants who are members of the industrial community they serve.

New Plant Construction

Among recently reported plant-construction programs related to National Defense activity are the following:

General Electric Company. Plans have been announced for the construction of two new plants for the manufacture of propulsion equipment for merchant ships. The plants will be financed by the Defense Plant Corporation under a lease agreement at a total cost of between $20,000,000 and $25,000,000. The larger, for manufacture of turbines, will be located in Erie, Pa.; the other, at which reduction gears will be made, will be at Lynn, Mass. Together the plants will total about 475,000 square feet of floor space. The company also has announced plans for the construction of a $20,000,000 factory at Fort Wayne, Ind., for the manufacture of turbosuperchargers for airplanes, now being carried on at Lynn, Mass. Location of the factory reflects the War Department policy of locating defense production plants inland. The building, one story high, will have about 400,000 feet of floor space. A $5,000,000 plant for the same type of manufacture is being completed at Everett, Mass. This is a one-story windowless "black-out" plant of 225,000 feet of floor space, lighted by fluorescent lamps providing 50 foot-candles uniform illumination throughout the plant, and completely air-conditioned.

Westinghouse Electric and Manufacturing Company. A $22,000,000 plant for the manufacture of steam turbines and gears for merchant ships is to be built adjoining the South Philadelphia works of the Westinghouse company, under an agreement with the Defense Plant Corporation. An additional expansion program of its Mansfield, Ohio, plant is also announced by the company; it will include a $240,000 addition to the present vitreous enameling building and a new enameling furnace.

Johns-Manville Corporation. Contract has been signed with the War Department for the construction and operation of a $27,000,000 shell-loading plant, to be located near Parsons, Kans., and known as the Kansas Ordnance Plant. The plant will include about 400 buildings, cover some 25 square miles, and employ about 8,000 persons. Operations will be conducted by a subsidiary company known as the J-M Service Corporation. Costs, including working capital, will be supplied by the Government. Construction is expected to require a year.

American Steel and Wire Company. Expansion of facilities at the company's plants at Joliet and Waukegan, Ill., will include construction of a new coarse rod mill and a new mill for manufacture of merchant products at Joliet, involving over 1,000,000 square feet of additional floor space. Expansion of manufacturing and storage facilities at Waukegan will add about 183,000 square feet.

College Administrators Confer With Defense Officials

Under the auspices of the subcommittee on military affairs of the National Committee on Education and Defense, 39 administrators representing eight national college and university associations met by invitation with National Defense officials in Washington, D. C., July 30–31, 1941. The purpose of the conference was to provide colleges with a comprehensive understanding of defense needs, both military and non-

New Plant Will Provide 300 Per Cent More Capacity

THE American Lava Corporation's new plant, now nearing completion at Chattanooga, Tenn., will provide a 300 per cent increase in capacity for one of the largest steatite insulator plants in the United States. The new ceramic plant, architect's drawing of which is shown here, is built of ceramics: glass block, brick, reinforced concrete. Large areas are air-conditioned and the whole plant has complete dust controls. Wherever possible, automatic control units are a part of equipment. All equipment has been secured and personnel trained. Walls are literally being built around the new equipment, and as sections of the building are completed, production gets under way. Emphasis on research and development is reflected in four new laboratories—electrical, mechanical, chemical, and testing. The plant is expected to relieve a scarcity of technical ceramics, particularly in steatitic high-frequency insulators.

military, as a basis for determining how their extensive physical plant and equipment and highly skilled personnel may be utilized to the fullest possible extent in the national interest. Three sessions were held: one with representatives of the Army and Navy, one devoted to potential service of the colleges in solving personnel and training problems for nonmilitary defense agencies, and one on civilian defense.

A summary of some of the important topics discussed appeared in the bulletin "Higher Education and National Defense" issued by the American Council on Education, and is contained, in slightly condensed form, in the following paragraphs.

The broad scope of the defense program and its potential effect on all civilians and civilian agencies were discussed by the various representatives of governmental agencies. With an increase from $30,000,000,000 in March 1941 to appropriations authorized or pending of $61,000,000,000 on July 31, 1941, demands for materials and personnel are staggering. At its peak this expanded production program will employ 30,000,000 men, whereas about 5,000,000 are now employed in defense industries. The Army will need 60,000 college-trained men and the Navy 11,000 for flying schools alone. For the short courses of college grade included in the Engineering Defense Training program (*EE, Sept. '41, p. 460*) an additional $17,500,000 has been appropriated. Last year the Civil Service Commission placed more than 500,000 persons in governmental service. Such facts as these will necessarily influence the development of higher education.

However, it was apparent that all governmental agencies recognize that education as such is national defense; that it is of vital importance to maintain a continuous supply of men and women trained in mind and body; that the college, through more effective instruction and guidance, can make a most important and necessary contribution to national defense; and that governmental agencies favor "the continued operation of educational institutions with as little disruption as possible, and have not attempted in any way to advocate or sponsor a reorienting of college courses."

The mechanization of military defense and the expansion of industry require increasing emphasis upon mathematics, science, and technical skills; however, it was emphasized that "The needs of total defense require that the individual student maintain a balance between technical–scientific training and a knowledge and appreciation of basic social and economic life."

To meet the existing great need for men—and the increasing need for women—with specialized training, governmental units propose to ask various institutions specifically for such training, rather than to suggest that *all* institutions undertake specialized training. Even if lists of technical skills now required were provided to the colleges, these would be of little value, since conditions change so rapidly that the relationship between supply and demand cannot be maintained. It was suggested, however, that all students be urged to take one or more courses of defense value, perhaps on an extracurricular basis.

The demand for trained personnel places upon the colleges a heavy responsibility for improving their guidance of students, which should be aimed at combining the best long-range placement of individuals according to their aptitudes, with the development of information on the best adaptation of each individual's abilities to the emergency effort. It was recommended that institutions prepare rosters of students, faculty, and alumni, classified in terms of skills, which could be supplied to local or national industrial or defense agencies; and also that they keep students and alumni informed of changing personnel needs in the defense training program.

Attention was called to the expansion of engineering defense training to include short courses in chemistry, physics, and management, the latter taking in management training offered by nonengineering colleges; but it was emphasized that these courses are not a substitute for full professional training program.

To assist in effective classification of students inducted into military service, colleges and universities were urged to prepare brief statements of interests, aptitudes, and special abilities, which the students could present at the time of their assignment to duty.

College authorities were urged to discuss means of rendering most effective service in their communities with local officials of the Office of Civilian Defense and, in defense communities, with local officials of the United Service Organizations and with camp commanders.

The need of building and maintaining morale was emphasized throughout the conference. Concrete suggestions included:

1. Reorientation of social studies to face present problems.

2. Greater emphasis upon civilians' responsibility for voluntary service and self-discipline.

3. Establishment of student and community forums to discuss current issues pertaining to democracy and world problems.

The educational representatives urged governmental agencies:

1. To maintain a high degree of flexibility in national programs, so that they may be adapted to local institutions.

2. To utilise all available personnel without regard to race, color, nation of birth, creed, or sex.

Navy Needs Engineers

The United States Naval Service has urgent need for large numbers of young men holding degrees in electrical engineering, mechanical engineering, and metallurgy, according to announcement from the Bureau of Navigation. After completing a special program of training, covering a four-month period, men enlisted for this service are appointed, if qualified, as ensigns in the United States Naval Reserve. As not enough graduates with the degrees mentioned have been secured, the program has been extended to other college graduates who have completed courses in physics, trigonometry, and chemistry.

To be eligible to enlist as midshipmen and enter the special training course, applicants must be native-born, unmarried, male citizens of the United States, over 20 and under 28 years of age at time of enlistment; meet physical requirements for ensign in the United States Naval Reserve; possess a bachelor's degree from an accredited university or college, with credits including at least two one-semester courses in college-grade mathematics; meet certain other requirements. After being appointed Reserve midshipmen and during the period under instruction they will be paid at the rate of $780 a year, with food and certain equipment furnished. Further information may be obtained from the Bureau of Navigation, Navy Department, Washington, D. C.

POSITIONS TO BE FILLED THROUGH CIVIL SERVICE EXAMINATIONS

Notice of the following positions, which will be filled through civil service examinations, is published here as a service to members of the Institute. Application forms and full information as to requirements for examinations may be obtained from the secretary of the Board of United States Civil Service Examiners at any first- or second-class post office, or from the United States Civil Service Commission, Washington, D. C.

Technical and Scientific Aids. Men and women are needed to do research and testing in radio, explosives, chemistry, physics, metallurgy, and fuels. The jobs pay from $1,440 to $2,000 a year. Among Government agencies expected to utilize these aids are: Bureau of Agricultural Chemistry and Engineering, Department of Agriculture; Bureau of Mines, the Department of the Interior; and the Bureau of Standards, Department of Commerce; the War Department in its Quartermaster Corps, and the Navy Department in its laboratories. No written test will be given. Applicants will be rated on education and experience as shown in their applications, subject to corroboration. Applicants must show 14 units of high-school study unless additional experience is substituted for it. In addition, they must have had appropriate technical and scientific experience of high quality. Approved defense training courses may be substituted for part, or—where appropriate—all, of the experience, and appropriate college study for a major part of the experience requirement. Applications will be received until June 30, 1942. However, since many of these positions are connected with the National Defense Program, persons who are qualified for and interested in these positions are urged to apply at once.

Radio Mechanic-Technicians. Salaries ranging from $1,440 to $2,300 a year. Applications will be received until November 6, 1941. Applications must show appropriate training or experience in one or more of the following:

1. Paid experience in technical radio work such as radio repairman, operator, or electrician.

2. Technical study in residence at a radio school.

3. Resident study including courses in radio in a school of engineering or technology.

4. Completion of an approved Defense Training Course in any branch of radio work.

Limited credit will be allowed for routine experience in a restricted phase of radio work or for experience in repair work on home broadcast receiving sets. Part-time experience in jobbing repair work on home broadcast receiving sets will not be accepted as qualifying. Radio mechanic-technicians will perform various duties in connection with the construction, assembly, and repair of radio equipment, including all types of modern radio communication equipment.

Information Specialists. Needed by the Government in connection with every phase of national defense activity. In press and publications, and in radio, there are over 100 jobs to be filled in the various Government agencies. Salaries range from $2,600 to $4,600 a year. Persons with general experience in press and publications, or radio work, are needed, as well as persons with publicity experience in such specialized fields as: Foreign news reporting or editing, aeronautics, public health, conservation, economics, mining, agriculture, and engineering. For all the positions, applicants may substitute college study for part of the experience. No written test will be given. In connection with the radio option a voice test may be required of eligibles. Applications must be on file with the Commission's Washington office not later than October 23, 1941.

Planning Board Establishes Alaska Office

To correlate plans for territorial economic development in Alaska with defense plans and other national needs, the National Resources Planning Board has set up a regional office at Juneau, Alaska, according to recent announcement. To work with the regional office, a Territorial Planning Council representing major Alaskan interests is to be appointed by the Governor. The Board points out that with the establishment of the naval and military bases in Alaska required for National Defense, the population of the territory will increase rapidly. Various departments and agencies of the Federal Government are being asked to prepare plans for Alaskan development, which will be correlated by the Board and related to territorial plans through the advice of the Territorial Planning Council.

Aluminum Company Reduces Prices. The price of ingot aluminum has been reduced from 17 cents to 15 cents a pound on shipments made after September 30, 1941, the Aluminum Company of America has announced. Corresponding reductions are being made in the price of fabricated aluminum. When the company began production in 1891, aluminum sold at $8 a pound and the company's annual capacity was 9,000 pounds. Its present production capacity is approximately 760,000 pounds annually, and with the addition of four new plants for which contracts have been awarded by the Defense Plant Corporation, is expected to be approximately 1,100,000 pounds per year. The present price reduction, which marks the lowest price in the company's history, is the fourth reduction in 18 months, and is made in anticipation of economies resulting from increased capacity. Chief beneficiary from price reductions is the United States Government, since most aluminum today is used in defense production.

Engineer Corps Expanding. The United States Engineer Corps has increased during the past year from 800 officers and 7,000 enlisted men to 4,200 officers and 61,000 men—a rate of expansion almost twice that of the Army as a whole. Nearly 3,000 of the 8,000 engineer reserve officers have been called to duty. Despite expansion, the Engineer Corps is still less than a third of its 1918 size. It was expanded during the first World War from 256 officers and 2,200 men to a total of 11,175 officers and about 285,000 men, including National Guard and National Army troops.

REA Schedules Cut by Defense Needs. Present need of materials for defense purposes will necessitate sharp curtailment of the line-building program of the Rural Electrification Administration. When projects currently under construction and those for which funds are already earmarked are completed, schedules are to be reduced nearly 50 per cent, in accordance with a program worked out with REA by the civilian allocation division of the Office of Price Administration and Civilian Supply. Construction at present is about five months behind allocations.

Industry • • • •

Fuel Consumption Reports Show Record Lows in 1940

The coal rate in 1940 for the production of electric energy was the lowest ever recorded, according to a recent Federal Power Commission report "Consumption of Fuel for Production of Electric Energy, 1940."

"The production of electric energy by use of all types of fuel, except wood," the report states, "totaled 96,609,089,000 kilowatt-hours during the year while the consumption of coal and coal equivalent of oil and gas totaled 65,136,000 tons. From these figures the coal rate for the year is found to be 1.35 pounds per kilowatt-hour. This is the lowest coal rate ever recorded and compares with 1.39 pounds per kilowatt-hour for 1939."

The report adds that "this low rate was obtained in part at least by the higher efficiency of the new steam plants which were placed in service and higher plant factors, or rates of operation, with a consequent reduction in pounds of coal per kilowatt-hour generated."

In the accompanying table, fuel consumption data for 1940 are compared with similar data for 1939.

The amount of energy generated in 1940 by use of coal totaled 79,229,168,000 kilowatt-hours or 12,592,159,000 kilowatt-hours more than were produced by this fuel during the previous year. The energy generated by use of oil during the year totaled 6,297,807,000 kilowatt-hours or 1,077,498,000 kilowatt-hours less than during the previous year. The energy generated by consumption of gas totaled 11,082,114,000 kilowatt-hours or 705,757,000 less than in 1939.

Type of Fuel	Unit	Amount Consumed 1940	Amount Consumed 1939	Change in Per Cent
Lignite	Short ton	452,412	1,538,174	− 5.6
Anthracite	Short ton	2,425,134	2,243,984	+ 8.1
Bituminous	Short ton	49,520,585	42,441,038	+16.7
All coal	Short ton	53,398,131	46,223,196	+15.5
Oil	Barrel	16,771,809	17,423,456	− 3.7
Gas	MCF.	183,157,400	191,130,940	− 4.2

In all instances the figures showing the kilowatt-hours produced represent the net station output after making deductions for energy used in the operation of equipment within the plant, the report explains.

PORT WASHINGTON SETS RECORD

The five-year performance record of the Port Washington station of the Wisconsin Electric Power Company, published in *Electrical World* (August 9, 1941 issue) shows an average coal rate over the five-year period 1936–40 of 0.83 pound per kilowatt-hour. For 1940 the coal consumption rate of the station reached a low of 0.825 pound per kilowatt-hour; in 1936 it was 0.84 pound. Port Washington is

Roebling Company Celebrates 100th Anniversary

Demonstration of the breaking of a four-inch wire rope at a pull of about 800 tons, was a feature of the 100th anniversary celebration of the John A. Roebling's Sons Company, Trenton, N. J. Watching the demonstration are some 85 trade editors and publishers. Speakers at the centenary dinner, held at Princeton, N. J., September 19, 1941, included W. A. Anderson, president of the company, and U. S. Price Administrator Leon Henderson. Among the achievements of the company, which was founded by John A. Roebling in 1841 at Saxonburg, N. J., are the suspension bridge across Niagara Falls built in 1850; Brooklyn Bridge, completed in 1883; and more recently the cables for the George Washington Bridge, and for the Golden Gate Bridge across San Francisco Bay.

known as "the world's most efficient station". Its gradual improvement in heat rate over the five years it has been in operation is attributed to improving the efficiency of auxiliary equipment; more favorable loading of the plant as system load increased, and, in 1940, reduction in the amount of hydroelectric power sent into the system from interconnections; and increased experience on the part of operators.

FPC Reports on Installed Water Power

A report entitled, "Installed Water Power in the United States and Outlying Territories—January 1, 1941," recently issued by the Federal Power Commission, covering plants of 100 or more horsepower, shows that the total installed capacity of water-power plants in the United States and the outlying territories was 19,015,101 horsepower at the beginning of the year.

The total capacity for the United States on that date, the report shows, was 18,868,027 horsepower, a net increase of 367,773 horsepower over total capacity reported January 1, 1940.

Largest net increases in installed water capacity during 1940 were in the following five states: Tennessee, 106,125; North Carolina, 78,945; Oregon, 72,875; Pennsylvania, 42,424; and New Mexico, 34,390 horsepower.

The annual increase in installed capacity of water wheels since January 1, 1926, has varied between 4,100 horsepower in 1935 and 1,275,530 in 1928. The average annual increase for the 15 year period, January 1, 1926, to January 1, 1941, is approximately 513,000 horsepower.

The table at the right shows installed water power capacity as of January 1, 1941, for the United States, geographic divisions, individual states, and outlying territories in total and by type of ownership.

Of the total water-power capacity in plants of 100 horsepower or over in the United States, 88.8 per cent or 16,747,053 horsepower is installed in plants having 5,000 horsepower capacity and over; 8.3 per cent or 1,574,552 horsepower is installed in plants from 1,000 to 5,000 horsepower capacity; and the remaining 2.9 per cent or 546,422 horsepower is installed in plants of from 100 to 1,000 horsepower capacity.

In terms of the number of plants, however, the situation is reversed, the report shows. Of the total number of plants of 100 horsepower or more in the United States 57.6 per cent or 1,613 plants were in the group with capacities between 100 and 1,000 horsepower; 24.6 per cent or 688 plants were in the group with capacities from 1,000 to 5,000 horsepower; and 17.8 per cent or 500 plants were in the group with capacities of 5,000 horsepower and over.

During 1940 seven major hydroelectric installations were placed in operation, of which five were Federal projects, and two were installations made by privately owned electric utilities. The individual capacities of these seven major installations are detailed in the preceding tabulation.

Copies of the report may be obtained at 10 cents a copy from the Federal Power Commission, Washington, D. C. Orders should enclose remittance; stamps are not acceptable. For convenience in ordering, the report may be referred to as FPC S-14.

Major Hydroelectric Generating Capacities Added in 1940

Installation	Horsepower
Federal Projects	
Bureau of Reclamation:	
Boruneville	74,000
Elephant Butte	34,500
Lower Colorado River Authority:	
Austin	20,000
Tennessee Valley Authority:	
Chickamauga	108,000
Hiwassee	80,000
Total	316,500
Private Companies	
Central Maine Power Company	34,000
Safe Harbor Water Power Company	42,500
Total	76,500

Installed Water Power Capacity in the United States, January 1, 1941

Plants of 100 Horsepower or More

Division and State	Total: Number of Plants	Total: Capacity in Horsepower	Publicly and Privately Owned Electrical Utilities: Number of Plants	Publicly and Privately Owned Electrical Utilities: Capacity in Horsepower	Industrial and Miscellaneous: Number of Plants	Industrial and Miscellaneous: Capacity in Horsepower
United States	**2,801**	**18,868,027**	**1,527**	**16,773,622**	**1,274**	**2,094,405**
New England	811	1,976,626	250	1,372,581	561	604,045
Maine	184	637,527	62	344,097	122	293,430
New Hampshire	149	478,537	53	367,613	96	110,924
Vermont	126	267,911	70	250,018	56	17,893
Massachusetts	214	388,911	38	256,113	176	132,798
Rhode Island	48	25,067	5	4,752	43	20,315
Connecticut	90	178,673	22	149,988	68	28,685
Middle Atlantic	455	2,467,431	211	2,251,631	244	215,800
New York	388	1,843,787	174	1,640,826	214	202,961
New Jersey	20	16,341	5	12,048	15	4,293
Pennsylvania	47	607,303	32	598,757	15	8,546
East North Central	417	1,221,319	298	1,044,856	119	176,463
Ohio	22	25,195	10	19,241	12	5,954
Indiana	29	53,117	20	47,284	9	5,833
Illinois	33	93,953	14	84,369	19	9,584
Michigan	159	533,865	132	493,625	27	40,240
Wisconsin	174	515,189	122	400,337	52	114,852
West North Central	183	869,559	135	762,531	48	107,028
Minnesota	64	262,420	46	176,422	18	85,998
Iowa	38	207,154	31	206,153	7	1,001
Missouri	8	247,253	7	247,103	1	150
North Dakota	0	0	0	0	0	0
South Dakota	10	19,463	5	6,500	5	12,963
Nebraska	47	120,250	37	117,089	10	3,161
Kansas	16	13,019	9	9,264	7	3,755
South Atlantic	305	3,492,619	156	2,861,047	149	631,572
Delaware	2	1,000	0	0	2	1,000
Maryland	6	404,437	3	402,248	3	2,179
District of Columbia	3	6,030	0	0	3	6,030
Virginia	61	282,301	44	258,685	17	23,616
West Virginia	12	307,615	10	161,515	2	146,100
North Carolina	104	1,033,320	45	655,444	59	377,876
South Carolina	57	338,549	22	791,845	35	46,704
Georgia	56	597,609	28	569,542	28	28,067
Florida	4	21,768	4	21,768	0	0
East South Central	50	1,991,137	35	1,808,620	15	182,517
Kentucky	8	151,431	4	150,300	4	1,131
Tennessee	28	694,406	19	525,255	9	169,151
Alabama	14	1,145,300	12	1,133,065	2	12,235
Mississippi	0	0	0	0	0	0
West South Central	34	218,292	31	217,697	3	595
Arkansas	5	95,060	5	95,060	0	0
Louisiana	0	0	0	0	0	0
Oklahoma	3	2,772	3	2,772	0	0
Texas	26	120,460	23	119,865	3	595
Mountain	253	2,390,486	190	2,366,418	63	24,068
Montana	23	501,857	19	499,647	4	2,210
Idaho	68	393,417	44	385,288	24	8,129
Wyoming	13	99,503	13	99,503	0	0
Colorado	56	110,824	28	99,359	28	11,465
New Mexico	7	35,683	6	35,564	1	119
Arizona	15	427,400	14	427,090	1	310
Utah	61	142,972	56	141,137	5	1,835
Nevada	10	708,830	10	708,830	0	0
Pacific	293	4,240,558	221	4,088,241	72	152,317
Washington	76	1,214,504	51	1,143,624	25	70,880
Oregon	78	587,793	53	525,828	25	61,965
California	139	2,438,261	117	2,418,789	22	19,472
Outlying Territories						
Alaska	30	46,082	9	13,005	21	33,077
Hawaii	29	31,768	10	16,795	19	14,973
Philippine Islands	4	26,680	4	26,680	0	0
Puerto Rico	13	42,544	13	42,544	0	0
Total	76	147,074	36	99,024	40	48,050

Destruction of Dnieperstroy Dam Officially Reported

Reports of the "complete destruction" of the Dnieper River dam and powerhouse by Soviet engineers to check the German advance have been officially confirmed from Moscow. Details of the destruction of the dam have not been made available.

The great Dnieperstroy project was begun in 1927 and completed in 1932 under the supervision of an American engineer, the late Colonel Hugh L. Cooper. The structure consisted of a gravity section spillway about 2,500 feet long, extending across the river channel. The concrete structure was 130 feet thick at the base and about 140 feet high. Three navigation locks were on the east bank of the river. The powerhouse, which had a capacity of 746,000 horsepower, was on the west bank, at the lower end of a forebay crossed by the roadway bridge to the dam proper. The bridge piers were provided with ice skimmers to protect the intakes at the powerhouse. According to *Engineering News Record* (September 4, 1941), destruction of the bridge and the intake structure would destroy the powerhouse and turn a flood through that channel which would effectively check efforts to bridge the river; an alternative method of destruction would appear to be mining and blowing up the central portion of the spillway.

Consolidated Edison Installs New Turbine. One of the world's largest topping turbines, a 65,000 kilowatt high-pressure generating unit, was put into service at the Waterside Station of the Consolidated Edison Company of New York, Inc., last month, bringing the total generating capacity of the system to 2,632,000 kilowatts. The capacity of the machine is 30 per cent greater than either of the other two units at the Waterside station. The system's electric power reserve, the total generating capacity exceeding the peak load of 1940, is now more than 900,000 kilowatts, which is considered to be an ample surplus to take care of any new power demands that might arise in the territory in the next two years.

By-Product. From the sand, gravel, and rock excavated for use as aggregate in the concrete for Friant Dam, in the United States Bureau of Reclamation's Central Valley, Calif., project, gold has been recovered in the amount of $94,520, according to a recent announcement. Gold recovery has averaged nearly $10,000 per month; expenses involved, including construction of the extraction plant, totaled $18,534. Net gold proceeds are equally divided between the contractor and the Government.

Missouri Passes Engineer Registration Law. Registration of engineers and architects in Missouri will begin October 10, as a result of a law recently passed by the Missouri State Legislature. Missouri up to now has been one of the few states that have not had such a law. The act covers registration of men now practicing in either profession, and will be administered by a seven-man board consisting of three engineers, three architects, and a chairman who may be either engineer or architect.

Steam-Electric Plants Use Oil By-Products. Three steam-electric generating stations using refinery by-products as fuel will provied needed energy for three oil refineries on upper San Francisco Bay, Calif. The stations, which will supplement the power-production system of the Pacific Gas and Electric Company, are being built at the refineries of the Associated Oil Company, Avon, Calif.; Shell Oil Company, Martinez; and Union Oil Company, Olcum. Each plant will have three boilers, each rated at 200,000 pounds of steam per hour; a single 3,600-rpm turbine capable of developing more than 50,000 kw; and a 40,000-kw 3,600-rpm hydrogen-cooled generator. The fuels used will be natural gas, oil, sludge (from the end of the oil-refining cycle), pitch (from the end of the gasoline-cracking cycle), and probably petroleum coke.

Radio Experts Study Vehicle Ignition Interference. Ignition systems in motor vehicles have been found to be the source of serious interference in short-wave radio broadcasting and television, according to radio experts of the United States Department of Commerce. Special committees set up by the American Standards Association and the Radio Manufacturers Association are considering ways and means of eliminating this interference, and tests and measurements have been made to determine the extent of interference from varying types of ignition systems. Electrical equipment used by the medical profession creates similar interference, this being especially noticeable in a building where several physicians have such equipment installed.

Brown Boveri Founder Dies. Sidney Brown, engineer, and founder of the Brown Boveri Company, Switzerland, died August 1, at Baden, Switzerland. He was 67 years old.

Other Societies •

NRC Engineering Division Transfers to Washington, D. C.

Increasing concentration of technical research activities in the national defense program has caused the transfer of headquarters for the National Research Council's Division of Engineering and Industrial Research from the Engineering Societies Building, New York, N. Y., to Washington, D. C.

The National Research Council was organized under the auspices of the National Academy of Sciences, as a result of an executive order from President Wilson in 1916 directing the formation of a body of scientists and technologists to mobilize technical talent for the national defense program then in progress. NRC came into being in 1917, following the entry of the United States into the first World War. After the armistice of November 11, 1918, the Council's Division of Engineering and Industrial Research began to concentrate its efforts on industrial technology, establishing its offices in New York City, for convenience of contact with engineers and the centers of operation of many industries.

The chief function of the Division in the present emergency, as seen by its executives, is to serve as a clearing house for information between the various defense agencies and United States engineering and industry. It also is active in organizing special committees and in finding qualified individuals to study special technical problems related to defense.

NRC Insulation Conference to Be Held in Williamsburg, Va.

The 14th annual meeting of the conference on electrical insulation of the National Research Council, division of engineering and industrial research, originally scheduled to be held at Washington, D. C., will take place in Williamsburg, Va., October 30–November 1.

Dielectrics in general will be the subject of several papers dealing with such questions as polarization parameters, variation in susceptance and dielectric loss at frequencies from 1 to 50 megacycles, a-c–d-c correlation, influence of sulphur and nitrogen on power factor, and dielectric constant and loss in the range of centimeter waves.

Special dielectrics will be represented in reports on the dielectric strength and life of impregnated paper, and cables will be discussed in papers on elevated temperature aging, semi-conducting shielding, and impulse strength. Other subjects to be treated are: effect of corona deposit on flashover voltage; electrical resistance of semiconductors; and the theory of an electric hygrometer. Discussion of problems arising from actual or potential shortages of certain insulating materials will be included on the program.

Copies of the program may be obtained by writing secretary of the conference Thorstein Larsen, Consolidated Edison Company of New York, Inc., 55 Johnson Street, Brooklyn, N. Y.

Future Meetings of Other Societies

American Institute of Chemical Engineers. 34th annual meeting, November 3–5, 1941, Virginia Beach, Va.

American Society of Civil Engineers. Fall meeting, October 15–17, 1941, Chicago, Ill.

Annual Meeting, January 21–22, 1942, New York, N. Y.

American Society of Mechanical Engineers. Fall meeting, October 12–15, 1941, Louisville, Ky.

Annual meeting, December 1–5, 1941, New York, N. Y.

American Welding Society. 22nd annual meeting, October 19–24, 1941, Philadelphia, Pa.

National Electrical Manufacturers Association. Annual meeting, October 27–31, 1941, New York, N. Y.

National Metal Congress. October 20–22, 1941, Philadelphia, Pa.

Society of Automotive Engineers. National aircraft production meeting, October 30–November 1, 1941, Los Angeles, Calif.

National transportation and maintenance meeting, November 13, 14, 1941, Cleveland, O.

Symposium on Insulation Materials Sponsored by NRC Chemistry Committee

UNDER joint auspices of the committee on chemistry, Conference and Electrical Insulation, of National Research Council, and the division of industrial and engineering chemistry of the American Chemical Society, a symposium on electrical-insulation materials was held September 11, 1941, at Atlantic City, N. J. R. N. Evans, chairman of the NRC committee who presided at the meeting, has provided the following brief abstracts of the six papers presented.

Influence of Oxidation on Dielectric Properties of Hydrocarbons and Hydrocarbon Oils, *J. C. Balsbaugh* (*A'23, M'35*), *A. G. Azzaf, J. L. Oncley.* In order to understand better the effect of oxidation upon the dielectric properties of hydrocarbon oils, an investigation of the behavior of various pure hydrocarbons has been carried out. Cetane has been extensively studied in the presence of copper, paper, both copper and paper, and without copper or paper. Whenever copper was present, it was found that very high losses, due to high d-c conductance, were obtained with very small amounts of oxygen, this loss dropping to a very low value with the absorption of further oxygen. Cetane in the presence of copper showed a similar high loss with a small amount of oxygen, but the loss remained very high with continued oxygen absorption. In contrast to this behavior, cis-decalin in the presence of copper and paper, and *n*-decane in the presence of copper showed very small losses even with quite large amounts of oxygen. Measurements of the dielectric constants of these hydrocarbons during oxidation, and measurements of conductance and dielectric constant as a function of frequency on a paper-oil combination (cetane and cis-decalin) showed a different oxidation mechanism in the initial stages of the oxidation of cetane from that of the later stages of cetane and from that shown by the other hydrocarbons. Measurements on a group of commercially refined oils showed characteristics similar to those of the hydrocarbons. These oils were studied under limited-oxidation conditions; the results showed that under such conditions relatively high conductivities or power factor may be obtained.

Paper Dielectrics Containing Chlorinated Impregnants—Deterioration in D-C Fields, *D. A. McLean, L. Egerton, G. T. Kohman, and M. Brotherton.* Chlorinated aromatic hydrocarbons are used extensively as impregnants for paper in electrical apparatus such as capacitors and transformers. They possess high stability toward heat and oxygen, noninflammability, and desirable electrical properties. However, the present study shows that under special conditions a type of decomposition occurs which liberates products so active chemically that, especially at elevated temperatures, under high potential gradients, and in contact with metals, autocatalytic decomposition reactions are initiated. When aluminum electrodes are used and d-c fields are applied, the deterioration manifests itself in a leakage current increasing with time and in the formation of partially carbonized areas in the paper. Evidence is presented that the decomposition starts by the splitting off of hydrogen chloride from the chlorinated compounds. This attacks the electrodes to form aluminum chloride, which in turn decomposes the organic constituents of the insulation. The deterioration is considered in relation to certain variations in composition, it being found that all components of the structure, the paper, the impregnant, and the electrode materials, play important roles in the reactions.

The Influence of Refining Technique on the Electrical Stability of Mineral-Oil-Treated Dielectrics, *F. M. Clark* (*A'24*) *and E. L. Raab.* The practical problems involved in the successful commercial application of mineral-oil-treated dielectrics concern the ability of the impregnating oil to withstand dielectric deterioration under normal conditions of oxidation and voltage stress. Unlike many of the other commercial applications of mineral oil, oil-treated dielectrics are expected to have an indefinite life in service. Minor but cumulative changes, therefore, may be of major importance. Such changes ultimately result in heat accumulation and final dielectric failure in accordance with pyroelectric principles. The chief cause of this dielectric deterioration is oil oxidation. Mineral oil of Gulf Coast crude can be greatly modified by changes in the temperature, and concentration of the sulfuric acid used in its refining. To obtain the greatest dielectric stability of the treated insulation, the oil is preferably refined at a temperature of 15 to 20 degrees centigrade using 96 per cent concentrated sulfuric acid. The preferred amount of acid used is approximately four pounds per gallon. Attempts to reduce the quantity of the acid by resort to higher treating temperatures gives a product of impaired stability.

The problem of oil refining for dielectric application is largely the problem of olefin removal without a major reduction in the content of aromatic hydrocarbons, the presence of which is necessary in order to obtain the maximum stability. The problem is made more difficult since there appears to be no oil property that can be used to predict the suitability of the oil for dielectric-impregnating use. The actual measurement of the type and amount of unsaturation present in the oil has been found to be the best guide for predicting the dielectric stability of the oil-impregnated insulation. For a Gulf Coast crude oil, the most stable product has been obtained when the refining treatment has been so controlled as to produce an oil having an aromatic unsaturation value in the range from 21.5 to 23 per cent and an olefin content less than 4 per cent.

The Theory of Dielectric Loss in Polar Polymers, *J. G. Kirkwood.* The dipole moment of a polar polymer, for example, polyvinyl chloride, depends on the internal configuration of the molecule. Under the influence of an applied electric field the molecules of the polymer diffuse by internal rotatory Brownian motion toward statistical equilibrium with the field, in which each molecule acquires a nonvanishing average electric moment contributing to the macroscopic dielectric polarization of the specimen. Associated with this internal rotatory diffusion is a spectrum of relaxation times corresponding to the different possible modes of coiling and uncoiling of the polymer chain. Due to these relaxation times, the polarization response of the molecule to an alternating electric field possesses a component out of phase with the field and the corresponding displacement current consequently has a nonvanishing conductance component. For molecules possessing a very large number of internal degrees of rotational freedom, the relaxation time spectrum may be approximated by a continuous relaxation time distribution, which determines the loss factor–frequency curve of the polymer system. The theory of Fuoss and the author (*Journal of Chemical Physics*, volume 4, 1941, page 329) provides a general mathematical description of this physical situation. The theory permits certain deductions concerning the structure of a polymer from its loss factor–frequency curve, and it promises to be of use in specifying the structural characteristics a polymer must possess in order to exhibit desired electrical properties.

Dependence of Dielectric Loss on Molecular Weight in the System Polyvinyl Chloride—Diphenyl, *R. M. Fuoss.* The loss factor of polar polymers goes through a maximum, the location of which is determined by temperature, frequency, and concentration of plasticizer for a given polymer. The absorption is due to the presence of the polar groups on the polymeric chain; in contrast to polar liquids, the dispersion range is very wide for the polymers, and a distribution of relaxation times, rather than a single relaxation time, is necessary for a description of their electrical properties. The most probable relaxation time, which is given by ($1/\omega_T$) times the reciprocal of the frequency of maximum absorption, is theoretically proportional to the number of monomer units in the chain, that is, to the degree of polymerization. Polyvinyl chloride was fractionated by dissolving it in a mixture of mesityl oxide and acetone, and precipitating by addition of successive portions of methyl alcohol. The fractions obtained were refractionated, to give polyvinyl chloride samples covering a range of three to one in average molecular weight as determined by their intrinsic viscosities. These samples were plasticized with 20 per cent by weight of diphenyl, and their electrical properties were determined at several temperatures over the frequency range 60 cycles to 10 kilocycles. The times of relaxation obtained from the data were proportional to the intrinsic viscosities, in agreement with theory. Measurements were also made on unfractionated polymers, covering a range of six to one in average molecular weight. They also gave most probable relaxation times proportional to average molecular weight. The difference between the electrical properties of fractionated and unfractionated polyvinyl chloride is rather small, because any chain gives a very broad distribution of relaxation times, and a superimposed distribution of chain lengths broadens the loss factor–frequency curve only a little more. The data also show that the average moment per monomer unit is independent of the degree of polymerization in fractionated polymers, and is independent of molecular weight distribution in polydisperse polymers.

The Relation of Dielectric Properties to Structure of Linear Polyamides and Polyesters, *W. A. Yager, W. O. Baker.* The dielectric constant and its related loss constituent, ϵ'', have been determined for the frequency range one kilocycle to 50 megacycles for polyesters of compositions varying the concentration of polar groups in the methylene units about fourfold, and for polyamides about twofold. Striking structural differences in the two series are reflected by the nearly frequency-independent $\epsilon' = 4.2$ and low ϵ'' for polyethylene sebacate, contrasted to polyhexamethylene adipamide, with the same concentration of polar groups along the chain. In the latter ϵ' decreases continuously with increasing frequency from 4.3 at one kilocycle, and ϵ'' shows a broad maximum at about 50 kilocycles. Further, the polyester results do indicate the incidence of a similar absorption maximum at frequencies above the upper limit of the reported range, perhaps in the very far infrared. Thus, hydrogen bonding in the polyamides may so constrain the motion of the polar groups, at 25 degrees centigrade, that small oscillating units exhibiting dispersion at 10^8 or 10^9 cycles in the polyesters behave similarly at only 10^4 to 10^5 cycles in the polyamides. Such specific interchain forces in the polyamides, their modification in the polyesters, the dielectric behavior of the bonding amido hydrogens, and the similar intrachain coupling in the two series indicate the electrical properties to be expected in more complex systems, such as the partially substituted cellulose derivatives. The mechanism of the dipole polarization and dispersion has been investigated by temperature variation of dielectric constant and loss of polyethylene sebacate and polyhexamethylene sebacamide. Interpretation of relaxation times from the absolute-rate theory has permitted estimation of the energy and entropy changes during dipole motion in the solid polymers.

ASA Adopts New Standard for Attachment Plugs and Receptacles

A new American Standard, *C*73-1941, "Standard for Attachment Plugs and Receptacles", developed over a period of 20 years by the National Electrical Manufacturers Association and its predecessor, the Associated Manufacturers of Electrical Supplies, has been approved by the American Standards Association. All manufacturers of attachment plugs, receptacles, and connectors use the specifications of the standard as the basis of their designs.

Because of a rapid increase in the use of portable electrical appliances in residences and commercial occupancies a single type of plug and receptacle for which the products of different manufacturers would be interchangeable was considered necessary. A study was made, and the standards for the flat-blade interchangeable type which had existed previously under the Associated Manufacturers of Electrical Supplies were codified in 1927. The present standard is a revision of the 1927 code. Further revisions will be made as needed. Copies may be obtained from the American Standards Association, 29 West 39th Street, New York, N. Y., at 30 cents per copy.

ASME Announces 1941–42 Officers

Officers of the American Society of Mechanical Engineers for 1941–42 have recently been elected. They are as follows:

President: James W. Parker, vice-president in charge of engineering, Detroit Edison Company, Detroit, Mich.

Vice-Presidents: Clarke F. Freeman, vice-president in charge of fire prevention engineering and underwriting, Manufacturers Mutual Fire Insurance Company, Providence, R. I.; Clair B. Peck, managing editor, *Railway Mechanical Engineering*, Simmons-Boardman Publishing Company, New York, N. Y.; William H. Winterrowd, vice-president, The Baldwin Locomotive Works, Eddystone, Pa.; and Willis R. Woolrich, dean of engineering, and director, bureau of engineering research, University of Texas, Austin, Tex.

Managers: William G. Christy, smoke abatement engineer, Hudson County Court House, Jersey City, N. J.; Herbert L. Eggleston, manager, gas and refining departments, Gilmore Oil Company, Los Angeles, Calif.; and Thomas S. McEwan, resident manager-engineer, McClure, Hadden and Orthan, Chicago, Ill.

Education • • •

Seminar Devoted to Ethics

In the College of Engineering at the University of Notre Dame the Dean meets weekly with the senior engineering and architectural students to discuss matters related to their professional development after graduation. Last year the first semester lectures were built around the topics representing the several functional divisions of work such as research, production, construction, etc., and were especially intended to give the students an inside into the type of work in which they might expect to find themselves during the first year or two after graduation; also to lay the foundation for subsequent consideration of related questions of ethics, citizenship, social responsibilities, etc. Second semester lectures were devoted to the investigation and consideration of professional ethics in the technical fields of engineering and architecture, supplemented by comparisons with other fields such as the legal, medical, and educational. Lectures by the dean were supplemented by those given by speakers selected from the ranks of practicing and professional men in the various fields. The codes of ethics issued by various national engineering and other societies were studied and discussed during the seminar period, and in the end the engineering students drew up the following "code of professional ethics of the 1941 Notre Dame engineers and architects":

1. Demonstrate honesty, sincerity, fairness, and honor in all of our professional dealings.

2. Abstain from all actions which, either directly or indirectly, would detract from the reputation, prospects, or professional undertakings of a fellow engineer.

3. Place our qualifications as engineers before the public in a dignified and conservative manner.

4. Consider information which concerns technical data, methods, or processes and business affairs as well as all information which is not common public knowledge, to be strictly confidential and not within our rights to divulge.

5. Direct our actions toward the best interests of public welfare and supply our knowledge, skill, and training for the use and benefit of mankind.

Northwestern University Buys Surge-Test Apparatus. Effects of lightning on all kinds of electrical equipment may be tested on comprehensive surge-test apparatus which is soon to be installed in the new Technological Institute at Northwestern University, Evanston, Ill. The lightning-making equipment consists of a 1,500,000-volt surge generator and a 500,000 volt-ampere, 60-cycle high-voltage test set. The lightning laboratory will be used for instructing students and for insulation research, and its facilities will also be available to public utilities in the Chicago area. It will be equipped to test insulation strength, and transformers, insulators, circuit breakers, and other electrical apparatus.

National Airport Conference. A national conference on airports, covering various aspects of airport construction, maintenance, and operation, will be held October 30–31, 1941, at Chicago, Ill., under the sponsorship of Illinois Institute of Technology. Speakers will include engineers, airline executives, and representatives of state and Federal agencies. According to announcement, Illinois Institute of Technology, which sponsors the annual Midwest Power Conference in the spring, plans to make the meeting on airports the first of a series of annual fall engineering conferences, each of which will center around a different subject of importance to the engineering profession.

Letters to the Editor • • •

INSTITUTE members and subscribers are invited to contribute to these columns expressions of opinion dealing with published articles, technical papers, or other subjects of general professional interest. While endeavoring to publish as many letters as possible, Electrical Engineering reserves the right to publish them in whole or in part or to reject them entirely. Statements in letters are expressly understood to be made by the writers; publication here in no wise constitutes endorsement or recognition by the AIEE. All letters submitted for publication should be typewritten, double-spaced, not carbon copies. Any illustrations should be submitted in duplicate, one copy an inked drawing without lettering, the other lettered. Captions should be supplied for all illustrations.

Relative Accuracy of Three-Phase Metering Combinations

To the Editor:

In connection with C. T. Weller's paper on "Relative Accuracy of Three-Phase Metering Combinations", (*Transactions pages 925–9*) which was read at the AIEE 1941 summer convention at Toronto, there was some verbal discussion of a suitable designation for the two-element, three-phase, four-wire meter.

Mr. Weller called it a "two-and-one-half-element meter" in his paper, following some recently started "popular" usage.

Such a term, I admit, has the advantage

of convenience, but it seems to me to be inconsistent and inadequate.

It is inadequate as descriptive of the meter, which in reality has only two elements, each element having a potential coil and two current coils.

To be consistent, a single phase, three-wire meter would have to be called a one-and-one-fourth-element meter; similarly, a two-element, three-phase, delta-supply, four-wire meter would be a two-and-one-fourth element meter, and a three-element meter for totalizing a three-phase and a one-phase, three-wire circuit would be a three-and-one-fourth element type.

The two-element meter for five-wire, two-phase circuits would also have to be another two-and-one-half-element meter, on the basis that it has the same arrangement of two current coils per element.

Thus, if the idea back of the "two-and-one-half-element" name were to be carried through, we would have an absurd terminology.

The object of this letter is to try to bring out some further views and suggestions as to suitable definitions for such meters, and to bring the matter in this way to the attention of the various committees active on definitions in the AIEE, the Edison Electric Institute, and the American Standards Association.

PAUL MACGAHAN (A'02, M'15)

(Development Engineer, meter department, Westinghouse Electric and Manufacturing Company, Newark, N. J.)

Youngest Subscriber?

To the Editor:

Enclosed is my check for $12.00 to cover a one-year subscription to ELECTRICAL ENGINEERING beginning with the October 1941 issue. This is to be sent to [my son].

This son is just starting his senior year in Brighton High School. He has been interested in electricity throughout his high school years and is past president of the high school Science Club. He hopes to enter M.I.T. next fall. [He] reads ELECTRICAL ENGINEERING and other electrical and technical publications at the Rochester Public Library and understands enough of the technical articles to make the reading worthwhile. He requested this subscription as a birthday gift, in preference to anything else.

Rotor-Bar Currents in Squirrel-Cage Induction Motors

To the Editor:

The paper by J. S. Gault on Rotor-Bar Currents in Squirrel-Cage Induction Motors" [*AIEE Trans. '41 (July), p. 784–91*] furnishes definite information on the actual action within the squirrel cage. However, one point does not seem to be brought out as prominently as it deserves. That is the amortisseur action of the squirrel cage which is always present in squirrel-cage motors. Although it is not confined to synchronous speed it can best be studied at this speed since various confusing factors then are eliminated.

An amortisseur resists sudden flux changes either as to position or density. Under the influence of a rapidly varying unidirectional magnetizing force it establishes a substantially constant average flux.

The squirrel cage at synchronism acts simply as an amortisseur winding. It provides an individual low-resistance short circuit enclosing each rotor tooth. Mr. Gault's data show that as the rotor moves in synchronism with the magnetic field it is subjected to rapidly varying unidirectional primary magnetizing forces that complete a cycle in each pole phase. Although the various rotor teeth are subjected to varying magnetizing forces, the amortisseur action holds the flux constant in each individual tooth; consequently the magnetic field is held constant both as to shape and intensity.

Since a cycle in the amortisseur currents is completed while the rotor moves one pole phase, their frequency in a three-phase motor is six times the fundamental frequency, in a two-phase motor four times, and in a single-phase motor, double.

The common assumption that there are no currents in the squirrel cage of a poly-phase motor at synchronism is shown to be in error. An appreciable I^2R synchronous rotor loss due to these amortisseur currents is possible.

Variations in the primary magnetizing forces increase as the number of phases decrease. The greatest variation occurs in the single phase where the primary magnetizing force varies all the way from zero to the maximum. This makes it necessary for the amortisseur currents to maintain the field while the primary magnetizing force goes through zero. In this case the double frequency amortisseur currents are very prominent and their I^2R losses are a substantial factor.

Mr. Gault presents a very clear picture of what actually takes place in the squirrel cage, thereby promoting a much better understanding of the various factors and their relations.

EDWARD BRETCH (M'19)

(Advance Electric Company, St. Louis, Mo.)

Induction-Motor Characteristics at High Slip

To the Editor:

In the AIEE TRANSACTIONS, volume 59, 1940 (August section), pages 464–8, T. H. Morgan, W. E. Brown, and A. J. Schumer give a method for measuring and studying the variation with slip, voltage, and current of such quantities as effective secondary resistance, stray load loss, torque, reactance, and so on, over the range of slip from 0 to 2. This accomplished, the paper then indicates that if certain readings are taken at the slips 0, full load, 1, and 2, it is possible to calculate the performance to be expected at other values of slip between 0 and 2 with greater accuracy than with the methods now in use. The paper indicates the procedure but requires the reader to arrange it into a working process.

RESULTS OF PAPER

In the belief that a restatement would be of service, the following is offered. The results of the paper indicate the following seven items.

1. *Skin effect*, etc., are sufficient to raise the secondary resistance markedly. This acts at high slips to increase that part of the torque due to secondary currents. Thus, in the 10 horsepower 60-cycle four-pole, three-phase 550-volt motor tested, the secondary resistance was

$$R_{sslt} = 0.74 + 0.103e^{0.01ns/3} \text{ ohms per phase}$$

2. *Stray iron load loss* varies as $(IS)^2$ regardless of whether the rotor moves with the internal torque or against it. This loss always acts as a brake so that it reduces the torque delivered to the shaft at $s<1$ and increases it at $s>1$. If W_l, I_l, S_l, represent tested values of stray load loss, primary current, and speed, with synchronism as unity, then the stray load loss at any other current I and speed S is given by

$$\frac{W}{W_l} = \frac{(IS)^2}{(I_lS_l)^2} = \left(\frac{I}{I_l}\right)^2\left(\frac{1-s}{1-s_l}\right)^2, \quad s=0 \text{ to } 2$$

3. *Shaft torque* consists of three components:

Copper,

$$T_{cu} = mI_2^2\frac{R_{sslt}}{s} = \frac{\text{rotor Cu. loss}}{s}$$

$$= \frac{\text{power converted}}{1-s}$$

Stray,

$$T_{ps} = \frac{W}{\doteq S} = \frac{W}{1-s}$$

Friction and windage

$$T_f = \frac{F\&W}{\doteq S} = \frac{F\&W}{1-s}$$

$$T = T_{cu} - T_{ps_l} - T_f$$

all in synchronous watts. Actual values of T observed at high slips have reached two or three times those calculated by conventional methods.

4. *Rotor copper loss*

$W_2 = mI_2^2R_{sslt}$
$= s \times$ air gap power.

5. *Air-gap power*

$P_g = \text{input} - mI_1^2r_1 - \text{no load iron loss}$

Optional values are

for $s<1$, $P_g = \dfrac{\text{shaft output} + F\&W + W}{1-s}$

for $s>1$, $P_g = \dfrac{\text{shaft input} - F\&W - W}{s-1}$

6. *Reactances* x, X_0. These may be determined by measurement from no-load and short-circuit tests (*EE, Mar. '40, p. 125*). They are considered constant.

7. *Secondary current* I_2. A convenient way to find I_2 from test is to obtain the no-load current I_0 and its power-factor angle θ_0, then for any primary load current I_1 and power-factor angle θ_1,

$$P_gP = \sqrt{(I_1\cos\theta_1 - I_0\cos\theta_0)^2 + (I_1\sin\theta_1 - I_0\sin\theta_0)^2}$$

$$= \sqrt{I_1^2 + I_0^2 - 2I_1I_0\cos(\theta_0 - \theta_1)}$$

$$I_1 = P_e P \times \frac{|Z_1|}{X_{12}} \cong P_e P \frac{\sqrt{r_1^2 + X_0^2}}{X_0 - \frac{x}{2}}$$

(considers N.L. core loss)

$$I_2 \cong \frac{X_{12}}{|Z_2|} I_1 \cong \frac{X_0 - \frac{x}{2}}{\sqrt{\left(\frac{r_2}{S}\right)^2 + X_0^2}} I_1$$

(neglects N.L. core loss)

TEST EQUIPMENT NEEDED

a. Motor whose performance is to be predicted.

b. Source of adjustable balanced three-phase voltage.

c. D-c and a-c electrical instruments for measuring input and output. Bridge for measuring stator resistance.

d. Source of d-c power.

e. Calibrated d-c machine with speed control, or electrical dynamometer of proper capacity.

f. Stroboscope for accurate slip readings.

ROUTINE MEASUREMENTS

If it were not for heating, the performance over the complete speed range could be determined by test with the equipment suggested. Because of this, performance readings are taken at four slips

$s = 2$, $s = 1$, $s =$ rated, $s \cong 0$

the first two at a voltage sufficiently low to prevent too rapid heating and the results referred to rated voltage by multiplying currents by $\frac{\text{rated } V}{\text{test } V}$; and input, output, torque, losses, etc., by the square of this ratio.

The readings will include d-c resistance of primary, temperature, voltage, currents, input, torque or output, slip, friction and windage. No-load iron loss

$F_{e1} =$ N.L. input $- m I_0^2 r_1 - F\&W$

These readings will be recorded on a laboratory test sheet. From these we shall have the values, referred to rated voltage as shown in the accompanying calculation.

PERFORMANCE CALCULATION

From the tests, we already have the points

$s \cong 0$, $s =$ rated, $s = 1$, $s = 2$

1 For other points, assume s.

2 From the three points in column 9, plot $R_{\text{eff}} = f(s)$.

3 Read R_{eff} from curve in 2, and obtain $\frac{R_{\text{eff}}}{s}$

4 Obtain x and X_0 (see item 6), and divide x into its components x_1 and x_2 (AIEE Induction Motor Standards), or use

$$X_1 \cong X_0,\ X_2 \cong X_0,\ X_{12} \cong X_0 - \frac{x_2}{2}$$

With the latter, the machine impedances are

5 $r_1 + jX_1 \quad = (\quad)$

6 $X_{12} \dfrac{3 - jX_0}{3^2 + X_0^2} = (\quad)$

Measure:

Slip	(1) Primary Input	(2) Shaft Torque Measured	(3) Shaft
$s = 2$	.....	T	Input $= T(s-1)$
$s = 1$	.....	T	0
$s =$ rated	.....	T	Output $= T(1-s)$

Calculate:

Slip	(4) Air Gap Power	(5) Power Converted	(6) Stray Load Loss
$s = 2$	Input $- m I_1^2 r_1 - F_{e1}$	$(4)(s-1)$	$W_t = (5) -$ shaft input $+ F\&W$
$s = 1$	Input $- m I_1^2 r_1 - F_{e1}$	0	0
$s =$ rated	Input $- m I_1^2 r_1 - F_{e1}$	$(4)(1-s)$	$W_t = (5) -$ shaft output $- F\&W$

Or alternately:

Slip	(7) Sec. Cu.	(8) Sec. Current	(9) R_{eff}	(10) Cu Torque	(11) Fe_2 Torque	(12) Stray Load Loss
$s = 2$	$2 \times (4)$	From equation	$\frac{(4)}{m \cdot I_2^2}$	$T_{Cu} \frac{(7)}{s}$	$TFe_2 = (2) - (10) - F\&W$	$W_t = \pm STFe_2$
$s = 1$	(4)	From equation	$\frac{(4)}{m \cdot I_2^2}$	$T_{Cu} \frac{(7)}{s}$	$TFe_2 = (2) - (10) - F\&W$	0
$s =$ rated	(4)	From equation	$\frac{(4)}{m \cdot I_2^2}$	$T_{Cu} \frac{(7)}{s}$	$TFe_2 = (10) - (2) - F\&W$	$W_t = \pm STFe_2$

7 $Z \underline{/\theta'} =$ Sum $= (\quad) = (\quad)$

Current

8 $I' = \dfrac{V}{Z \underline{/\theta'}} = I'(\cos\theta' - j \sin\theta') =$

$A' - jB'$ amp. per phase

9 $I_{Fe} = \dfrac{Fe_1}{mV} = (\quad)$ amp. per phase

10 $I_1 \underline{/\theta} = (\quad) = (\quad)$ amp. per phase

11 $I_2 \cong \dfrac{X_{12} I'}{\sqrt{3^2 + X_0}} = (\quad)$ amp. per phase

12 Input $= mVI_1 \cos\theta = (\quad)$ watts

Torque

13 $T_{Cu} = m I_2^2 \dfrac{r_2}{s} = (\quad)$ synchronous watts

14 $T_{F\&W} = \dfrac{F\&W}{\pm S} = (\quad)$ synchronous watts

15 $T_{Fe_2} = \dfrac{W}{\pm S} = (\quad)$ synchronous watts

16 $T = T_{Cu} - T_{F\&W} - T_{Fe_2} = (\quad)$
synchronous watts for $s = 0$ to 1
$T = T_{Cu} + T_{F\&W} + T_{Fe_2} = (\quad)$
synchronous watts for $s = 1$ to 2

17 Shaft output, $W_0 = (1-s)T = (\quad)$
watts for $s = 0$ to 1
Shaft input, $W_0 = (s-1)T = (\quad)$
watts for $s = 1$ to 2

18 Efficiency $= \dfrac{17}{12} = (\quad)$ for $s = 0$ to 1

19 Power factor $= \cos\theta$

20 Losses $=$ input $-$ output. For check:

Pri. Cu. loss $= m I'^2 r_1$	$= (\quad)$
Sec. Cu. loss $= m I_2^2 r_2$	$= (\quad)$
$F\&W$	$= (\quad)$
No load iron loss	$= (\quad)$
Stray load loss	$= (\quad)$
Total loss	$= (\quad)$

SYMBOLS

f_2 = rotor frequency in cycles per second
F_{e1} = "low frequency" iron loss in watts
F_{e2} = "high frequency" iron loss in watts
$F\&W$ = friction and windage loss in watts
I' = primary current when low frequency iron loss is omitted
m = number of primary phases
$r_2 = R_{\text{eff}}$ = effective resistance of secondary at slip considered in terms of primary, ohms per phase
s = slip as a decimal
$S = 1 - s$
V = primary impressed electromotive force in volts per phase
x = leakage reactance in ohms per phase
X_0 = no load magnetizing reactance in ohms per phase
X_1 = total reactance of primary with secondary open in ohms per phase
X_2 = total reactance of secondary with primary open in ohms per phase
X_{12} = mutual reactance between primary and secondary
= magnetizing reactance for air gap in ohms per phase
Z = impedance of machine at slip s in ohms per phase
$Z_1 = r_1 + jX_1$ = total impedance of primary in ohms per phase

Torque in pound-feet can be obtained from the relation

$$\text{Lb-Ft} = 7.04 \times \frac{\text{watts}}{\text{rpm}} = 7.04 \times \frac{\text{synchronous watts}}{\text{synchronous rpm}}$$

A. F. PUCHSTEIN (A'20, M'27)
(Consulting Engineer, Springfield, Ohio)

Books Received •

"The Colorado Conquest." This story of the 400-year struggle of men and machines against a river is written in a new form, described by the author as "a combination of carefully documented fact with equally documented dramatization." Tracing the history of the attempts to tame the Colorado River from the first ill-fated explorations of the Spanish *conquisladores* in 1540 to the completion of Boulder (Hoover) Dam in 1940, the book is a careful study of the engineering problems involved, but because of the excellent handling of the human element reads like a novel. The explorers, pioneers, and geographers who tried to find a safe way of crossing the treacherous canyons and deserts surrounding the Colorado to establish routes to the fertile West; the settlers who fought unceasingly to control the river's sudden and devastating floods and to use its waters for irrigation and electric power; the adventurers and politicians who looked for substantial profits if the river could be subdued; and finally, the engineers, who found its control a challenge to their ingenuity—all are skillfully combined into a good story. Dodd, Mead and Company, New York; 361 pages; $3.

"Guide to Library Facilities for National Defense." Revised. Data from about 250 additional libraries, and expansion of data on those originally included, increase the utility of this publication of the American Library Association, the first edition of which appeared late in 1940 and was reviewed in the April 1941 issue, page 189. Holdings of approximately 800 public, university, college, reference, governmental, industrial, and business libraries are described in this 411-page survey of library resources on subjects relating to defense. Material is arranged in a manner similar to the arrangement of the previous edition, except for the following changes: listing by states instead of large regions, under subject; directory information about libraries in text instead of in appendix; more main subject headings. Published in typewritten, lithographic form; may be obtained from the American Library Association, Chicago, Ill.

"New Encyclopedia of Machine-Shop Practice." This 548-page volume edited by George W. Barnwell contains chapters on many phases of machine-shop operation. Specific instructions and diagrams are included, describing the proper operation of machines, correct use of tools, and machine shop methods. The book may be used as a reference book or for study. It contains illustrations of many types of machines and parts, and tables of dimensions. Published by Wm. H. Wise and Company, New York, price $1.98 (de luxe edition $2.48).

"Elements of Electrical Engineering." Fourth edition, revised and rewritten. This book by A. L. Cook (A'02, M'13) dealing with the fundamentals of electrical engineering and their application in practice, is intended as a short course for electrical-engineering students, and also for other students in colleges. No attempt has been made to describe all types of electrical machinery, but rather an attempt has been made to give special attention to subjects not usually easily understood by students, such as magnetic circuits and a-c currents and machinery. Material is presented in a way calculated to bring out the physical significance of a result, and not to depend merely upon the mathematical derivation of a formula. The specific applications described and the problems used have been chosen to provide practice in identifying the fundamental laws upon which the operation of a machine is based. Published by John Wiley and Sons, Inc., New York; 611 pages; price $4.00.

"Abridged Scientific Publications From the Kodak Research Laboratories." Volume 22, 1940. This annual publication of the Kodak Research Laboratories is a compendium of articles in the field of photography and the allied arts which originated with the Laboratories and have been previously published in full in various scientific journals. These are given here in abridged form, only the more essential features and outlines being presented. Original place of publication is cited for each article. Indexed by subject and author. Published by the Eastman Kodak Company, Rochester, N. Y.; 278 pages.

"Molding Technic for Bakelite and Vinylite Plastics." Fourth edition. Published in the interests of molding material fabricators, this volume is designed as a handbook covering the art of molding plastic products. Important phases of molding processes and molding equipment employed generally in the commercial production of molded plastic parts are discussed. In keeping with the subject matter the book is mechanically bound, with a plastic spiral backbone. It is conveniently tab-indexed by chapter, with side-headings on the first page of each chapter, and also has an alphabetical index. Bakelite Corporation, New York; price $3.50.

"Surge Phenomena." Subtitled "Seven Years' Research for the Central Electricity Board (1933–1940)," this volume is published by the British Electrical and Allied Industries Research Association in order to present a study of surge phenomena from every aspect and especially under actual working conditions. In each case descriptions of instruments used, procedure, results and, in some cases improvements, obtained, are given in full. Phases of the field discussed include: the study of lightning; surge propagation; surge voltage distribution in transformers; effects of surges on insulation; and protection against surges. Illustrated, tables; 416 pages; price £2 10s.

"Directory of Microfilm Sources." This 56-page booklet compiled by R. C. Cibella lists libraries and commercial firms in the United States which have microphotographic equipment, microfilm projection equipment, microfilm collections, and special collections for microphotographing. Types of cameras or photographic machines, sizes of film available, types of material microfilmed, time required for filling orders, and prices for the services are given. Libraries and sources are listed alphabetically, and there is also a geographical index to enable the user to find the nearest institution having the necessary equipment or service. Published by the Special Libraries Association, 31 East Tenth Street, New York, N. Y.; price 75 cents.

"Trade Names Index." An alphabetical index of definitions of unusual trade names not indexed in better known sources, is presented in this 178-page book. The listing is based on material from the files of the Technology Department of the Carnegie Library of Pittsburgh. The index is concerned, in general, with definitions of materials, processes, and equipment of technical significance. In nearly all cases references are cited, and where possible a definition is given. A bibliography of other sources of information concerning trade names is also included, listed alphabetically by subject. Registered trade-marks published by the United States Patent Office are not included. Published by the Special Libraries Association, 31 East Tenth Street, New York, N. Y.; price $4.00 plus postage.

"Technology and Society. The Influence of Machines in the United States." This book by S. McKee Rosen and Laura F. Rosen is described by the publishers as being a "sound and not too technical consideration of the changes which machines and recent mechanical inventions have brought to life in the United States." Specific inventions are considered first, and then the economic, social, and political aspects of these inventions are discussed in three separate sections. In conclusion possible future ways of controlling the influence of technology on human life are suggested. Many tables and illustrations; 466 pages; The MacMillan Company, New York; price $4.00.

The following new books are among those recently received at the engineering Societies Library. Unless otherwise specified, books listed have been presented by the publishers. The Institute assumes no responsibility for statements made in the following summaries, information for which is taken from the prefaces of the books in question.

AUDELS NAW ELECTRIC SCIENCE DICTIONARY. By F. D. Graham. Theodore Audel and Company, New York, 1933. Reprinted 1939. 525 pages, 7 by 5 inches, cloth, $2.00. More than 9,000 words, terms, and phrases used in theoretical and applied electricity are defined in this dictionary. Numerous terms in related and independent subjects have been included to increase the utility of the work, and extended explanations are given for the more important entries.

AMOS EATON, SCIENTIST AND EDUCATOR, 1776–1842. By E. M. McAllister. University of Pennsylvania Press, Philadelphia, 1941. 587 pages, illustrated, 9½ by 6 inches, cloth, $5.00. Amos Eaton, who, with the backing of Stephen Van Rensselaer, founded what is now Rensselaer Polytechnic Institute, lived an eventful life. This well-documented biography describes his early life, his business and legal career, his ventures into the natural sciences, particularly geology, and his final success as an educator.

ATM (Archiv für Technisches Messen). Lfg. 116-117, 118, February, March, April 1941. R. Oldenbourg, Munich and Berlin, pages T16–30, F2; T31-46; T47–62; illustrated, 12 by 8½ inches, paper, 1.50 rm. each. Three numbers of a monthly publication containing classified articles upon various types of apparatus and methods for technical measurements. Some of the numbers also contain descriptions of specific instruments manufactured by German companies.

Transactions Section

Preprint of Corresponding Pages From the Current Annual Transactions Volume

Any discussion of these papers will appear in the December 1941 "Supplement to Electrical Engineering—Transactions Section"

Conductor Vibration—Theory of Torsional Dampers

JAMES W. SPEIGHT
NONMEMBER AIEE

Synopsis: The paper is a theoretical treatment of the torsional damper which has been applied effectively to the protection of transmission line conductors from fatigue failures due to aeolian vibrations. The formulae of the energy dissipation are derived for three cases, viz., a single rigid damper, two rigid dampers at one end of a span, and a single damper with a resilient joint at the centre of gravity. The results are valuable in understanding the mode of operation of the torsional damper and point to certain optimum features of design. The formulae can be used for numerical calculations when the physical constants are known.

Introduction

FOR many years, electric power companies have been investigating the protection of transmission line conductors from fatigue failures that result from the vibrations excited by steady cross winds of low velocity. The methods of protection that have been proposed are very diversified in character, including the prevention of the vibration at its source with conductors of non-circular cross section, the reduction of concentrated stresses at the clamp by the use of reinforcing cables or rods, and the suppression of the vibrations by the application of damping devices. An energy-absorbing damper has proven to be the most practical solution up to the present time, and has been adopted for a number of lines in North America. An estimate of the efficiency of such devices has been determined, in a few instances, by experimental field studies and, more frequently, by operating experience.

The Hydro-Electric Power Commission of Ontario with power lines of all sizes throughout the province has, of course, been vitally interested in the problem of aeolian conductor vibrations. The need for an effective solution has been most important in recent years since, in modern construction using long spans and high tensions, the conductor is subject to more severe conditions of vibration than in the older construction with short spans and low tensions. To study the effectiveness of various protective schemes, a method was devised for recording the natural vibrations of damped and undamped lines and for analyzing the results statistically. Such experimental data on the frequency characteristics of a type of conductor are essential for the proper design of a protective device for that particular type.

In the year 1935, the theoretical and practical studies indicated that the conductor itself was available to absorb energy, if a suitable restraining force could be applied to the conductor to utilize the interstrand friction and the mechanical hysteresis loss. This force was accomplished with an offset weight attached to the conductor by a horizontal arm, so that a torsional motion was produced between the suspension clamp and point of attachment of the weight when the conductor vibrated. Additional damping was obtained by mounting the offset weights in pairs adjacent to and at different distances from the suspension clamp, when, for most frequencies of vibration, the section of conductor between the two offset weights was also in torsional motion. The torsional device which has become known as a torsional damper has been developed considerably in the last five years and is now practical.

Torsional dampers have been installed for the suppression of aeolian vibrations on the latest ACSR lines built by the Hydro-Electric Power Commission of Ontario. A torsional damper designed for 795,000 cir-mil ACSR is shown in figure 1 and is constructed with a resilient joint of rubber. In California, a rigid type of torsional damper has been adopted for the protection of H-H copper conductor on the exposed sections of the Boulder Dam transmission line.

Theory

The theoretical development of the torsional damper was studied along with the experimental work, and it is the purpose here to derive the theoretical formulae. The formulae were of great assistance in bringing the torsional damper to its present form and are valuable in designing dampers for specific conductors and predicting the approximate performance. The analysis of the torsional damper is limited here to the condition of steady state vibration, and does not include other possible beneficial effects which might exist under initial transient conditions. The reaction of the damper on the motion of the conductor is not taken into account either, since, for the suppression of vibration, the energy dissipative capacity of the damper is of prime importance and is affected only by the amplitude of the motion at the point of attachment, all the other factors being constant. The application of the formulae to actual numerical cases is direct, provided that the requisite physical constants are available.

The mode of vibration at a given point of a line conductor in service usually has a beat characteristic and not a constant maximum amplitude. However, the generality of the analysis is not affected, if it is considered that the conductor vibrates like a perfectly flexible string under tension[1] having the motion

$$y = A_0 \sin (2\pi x/\lambda) \sin \omega t = A \sin \omega t \qquad (1)$$

Paper 41-94, recommended by the AIEE committee on power transmission and distribution, and presented at the AIEE summer convention, Toronto, Ontario, Can., June 16-20, 1941. Manuscript submitted January 29, 1941; made available for preprinting May 14, 1941.

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1. For all numbered references, see list at end of paper.

where

A_0 is the maximum amplitude
λ is the wave length
ω is the angular velocity $2\pi f$
f is the frequency

The differential equation for free torsional motion is

$$I\ddot{\theta}+q\dot{\theta}+\tau\theta=0 \tag{2}$$

where I is the moment of inertia and τ is the angular elastic constant.

With

$\alpha=q/2I$ and $\omega_c^2=\tau/I$

the solution is

$\theta=B_0e^{-\alpha t}\sin(\omega t+\phi)$

in which B and ϕ are constants and $\omega^2=\omega_c^2-\alpha^2$. If $\alpha\ll\omega_c$,

$\omega^2\approx\omega_c^2=\tau/I$

Therefore, the quantity q which will be defined as the "torsional resistance" is given by

$$q=\delta\tau/\pi\omega \tag{3}$$

because $\alpha=\delta f$ where δ is the logarithmic decrement.[3]

For a rod of circular cross section, the angular elastic constant is inversely proportional to the length of the rod.[2,3] Hence, it is evident from relation 3 that the torsional resistance of a conductor is increased by decreasing the length of the effective part of the conductor.

Single Rigid Damper

The position of a single rigid damper at any moment can be represented as in figure 2. The notation is

M = mass of damper
$I=MK^2/g$ = moment of inertia about the axis of the conductor
$I_G=Mk^2/g$ = moment of inertia about the centre of gravity
l = distance from the centre of conductor to centre of gravity
θ = angular displacement from the horizontal
$y=A\sin\omega t$ = displacement of the point of support
h = distance of centre of gravity from position of equilibrium
$K^2=k^2+l^2$

The velocity of the centre of gravity for small oscillations is $(\dot{y}-l\dot{\theta})$. Considering the transverse energy of the conductor to be independent of θ, the kinetic energy of the damper is

$S=M(\dot{y}-l\dot{\theta})^2/2g+I_G\dot{\theta}^2/2$

The potential energy associated with the torsional motion is

$$\tau(\theta+\theta_0)^2/2-\tau\theta_0^2/2=\tau\theta^2/2+Ml\theta \tag{4}$$

since θ_0 is the static rotation and $Ml=\tau\theta_0$. The increase in the gravitational potential energy of the mass is

$$Mh\approx M(y-l\theta) \tag{5}$$

Therefore, the potential energy function is, adding 4 and 5,

$V=\tau\theta^2/2+My$

The Lagrangian function is $L=S-V$ and, from Lagrange's equation[4]

$$\frac{d}{dt}\left[\frac{\partial L}{\partial\dot{\theta}}\right]-\frac{\partial L}{\partial\theta}=0 \tag{6}$$

it follows that, adding the dissipative term,

$$\ddot{\theta}+2\alpha\dot{\theta}+\omega_c^2\theta=l\ddot{y}/K^2 \tag{7}$$

Figure 1. Torsional damper for 795,000-circular-mil steel-reinforced aluminum cable

The steady state solution of differential equation 7 is

$$\theta=-\frac{lA\omega^2}{K^2Z}\sin(\omega t-\beta) \tag{8}$$

with

$Z^2=(\omega_c^2-\omega^2)^2+4\alpha^2\omega^2$

and

$\beta=\tan^{-1}[2\alpha\omega/(\omega_c^2-\omega^2)]$

The power dissipation is

$$P=\frac{1}{T}\int_0^T q\dot{\theta}^2dt$$
$$=ql^2A^2\omega^6/2K^4Z^2 \tag{9}$$

The graph of the frequency function $f^6/[\pi^2(f_c^2-f^2)^2+\alpha^2f^2]$ contained in equation 9 for constant amplitude is plotted in figure 3 with $f_c=5$ cps. and $\alpha=4$. Actually, most materials dissipate energy by solid damping[2] and then δ, not α, is constant with respect to frequency. From the curve, it is seen that to suppress a range of frequencies the damper has to operate on the region above f_a, i.e.,

$$\omega_a<\omega \tag{10}$$

In determining the damper spacing, the amplitude A which is a function of the frequency is considered in conjunction with the other factors. As a numerical example, let the velocity of propagation (λf) be 400 ft./sec. and the damper be 5 feet from the clamp. For a frequency range 5 to 20 cps.,

$1\geq\sin(2\pi x/\lambda)>0.38$

and the power loss at 20 cps. due to this

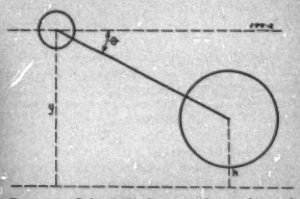

Figure 2. Schematic diagram of a single rigid damper in motion

factor is about seven times that at 5 cps. The magnitude of the divergence is reduced greatly, in practice, because the power loss associated with the transverse vibrations of a conductor excited by the wind increases rapidly with frequency and, consequently, the amplitude A_0 becomes smaller.[5] Thus, the spacing of 5 feet gives a satisfactory response to the frequency variations under these conditions.

If the condition $\omega_c\ll\omega$ is maintained, the optimum value of l is given by

$\frac{d}{dl}(P/K^4)=0$

or,

$$l=k \tag{11}$$

Then, the maximum power is

$P_M=qA^2\omega^6/8\beta^2Z^2$

from which it is deduced that the optimum optimum magnitude of l is the smallest value consistent with conditions 10 and 11.

For a damper with a heavy, concentrated mass and a long arm, $K\to l$; $\beta\to\pi$; $Z\to\omega^2$ and

$\theta=(A/l)\sin\omega t$

i.e., the centre of gravity remains stationary in space. This effect is observed in the field for the stated conditions. The power

dissipation for this case, substituting the value of q, becomes

$$P = b\gamma f A^2/l^2$$

Two Rigid Dampers at One End of Span

In figure 4, the arrangement of two dampers having the same physical dimensions is shown schematically for the horizontal plane. The notation of the previous section is adopted with the subscripts 1 and 2 referring respectively to dampers 1 and 2. The quantities τ_1, τ_2 and τ_3 represent the angular elastic constants for the three sections of the conductor between the clamps and the two dampers. The displacements at the points of attachment are

$$y_1 = A_1 \sin \omega t$$

$$y_2 = A_2 \sin \omega t$$

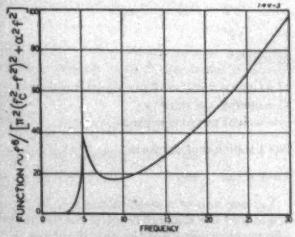

Figure 3. Graph of function for $f_0 = 5$ cycles per second and $\alpha = 4$

The kinetic energy of the system is

$$S = (M/2g)[(\dot{y}_1 - l\dot{\theta}_1)^2 + (\dot{y}_2 - l\dot{\theta}_2)] + I_G(\dot{\theta}_1^2 + \dot{\theta}_2^2)/2 \quad (12)$$

Disregarding the gravitational potential energy function which does not contribute to the motion, the potential energy is

$$V = \tau_1\theta_1^2/2 + \tau_2(\theta_1 + \theta_2)^2/2 + \tau_3\theta_2^2/2 \quad (13)$$

If the mutual torsional resistance is designated by q_3, the differential equations of motion with the dissipative terms are

$$\ddot{\theta}_1 + 2\alpha_1\dot{\theta}_1 + \omega_1^2\theta_1 + 2\alpha_3\dot{\theta}_2 + \Omega^2\theta_2 = l\ddot{y}_1/K^2$$

$$\ddot{\theta}_2 + 2\alpha_2\dot{\theta}_2 + \omega_2^2\theta_2 + 2\alpha_3\dot{\theta}_1 + \Omega^2\theta_1 = l\ddot{y}_2/K^2$$

with

$$\omega_1^2 = (\tau_1 + \tau_2)/I \quad \text{and} \quad \alpha_1 = q_1/2I$$

$$\omega_2^2 = (\tau_3 + \tau_2)/I \qquad \alpha_2 = q_3/2I$$

$$\Omega^2 = \tau_2/I \qquad \alpha_3 = q_3/2I$$

Making the substitutions

$$N_1 e^{j\beta} = A_1(\omega_1^2 - \omega^2) - A_2\Omega^2 + 2j\omega(\alpha_3 A_1 - \alpha_2 A_2)$$

$$N_2 e^{j\gamma} = A_2(\omega_1^2 - \omega^2) - A_1\Omega^2 + 2j\omega(\alpha_1 A_2 - \alpha_3 A_1)$$

$$De^{j\epsilon} = (\omega_1^2 - \omega^2)(\omega_2^2 - \omega^2) - \Omega^4 + 4\alpha_3^2\omega^2 - 4\alpha_1\alpha_2\omega^2 + 2j\omega[\alpha_1(\omega_2^2 - \omega^2) + \alpha_2(\omega_1^2 - \omega^2) - 2\alpha_3\Omega^2]$$

it follows that

$$\theta_1 = -\frac{l\omega^2 N_1}{K^2 D} \sin(\omega t + \beta - \epsilon)$$

$$\theta_2 = -\frac{l\omega^2 N_2}{K^2 D} \sin(\omega t + \gamma - \epsilon)$$

The power dissipated by the two dampers is

$$P = \frac{1}{T}\int_0^T [(q_1\dot{\theta}_1 + q_3\dot{\theta}_2)\dot{\theta}_1 + (q_2\dot{\theta}_2 + q_3\dot{\theta}_1)\dot{\theta}_2]\,dt$$

$$= \frac{l^2\omega^6}{2K^4D^2}[q_1N_1^2 + 2q_3N_1N_2\cos(\beta - \gamma) + q_2N_2^2] \quad (14)$$

It is interesting to observe that the second term may increase or decrease the energy loss depending on whether N_1 and N_2 have the same phase or opposite.

If the moment of inertia is large and the arm is relatively long, the following approximations hold

$$\left.\begin{aligned} N_1 &\to A_1\omega^2 \\ N_2 &\to A_2\omega^2 \\ D &\to \omega^4 \\ K &\to l \\ \beta &\to \gamma \to \pi \\ \epsilon &\to 0 \end{aligned}\right\} \quad (15)$$

Therefore, from equation 14,

$$P = \frac{\omega^2}{2l^2}(q_1A_1^2 + 2q_3A_1A_2 + q_2A_2^2) \quad (16)$$

From relation 13 and the fact that the logarithmic decrement is equal to the energy loss per cycle divided by twice the maximum potential energy,[2] the power dissipation for conditions 15 may also be written

$$P = \frac{\delta f}{l^2}[(\tau_1 + \tau_2)A_1^2 + 2\tau_3A_1A_2 + (\tau_2 + \tau_3)A_2^2] \quad (17)$$

The corresponding coefficients in expressions 16 and 17 are identical, so that the torsional resistances are

$$q_1 = \delta(\tau_1 + \tau_2)/\pi\omega$$

$$q_2 = \delta(\tau_2 + \tau_3)/\pi\omega$$

$$q_3 = \delta\tau_2/\pi\omega$$

Single Damper With Resilient Joint at Center of Gravity

The inherent damping in some conductors is not sufficient in itself to suppress the vibrations adequately, even with two rigid dampers. Supplementary damping is introduced then by making a resilient joint near the centre of gravity with a material of high damping such as rubber. To facilitate the analysis, the damper is assumed to have the joint at the centre of gravity as in figure 5. In practice, the dampers are installed at both ends of the span and the power dissipation per span is twice the derived formula.

The notation will be the same as before with the subscript r designating the physical constants of the resilient material. The kinetic energy at any moment is

$$S = Mk^2\dot{\theta}^2/2g + M(\dot{y} - l\dot{\theta})^2/2g$$

The potential energy is

$$V = \tau\theta^2/2 + \tau_r(\Phi - \theta)^2/2$$

The damping force of the resilient joint is proportional to the relative angular velocity $(\dot{\Phi} - \dot{\theta})$. Hence, the differential equations of motion including the dissipative terms become

$$\ddot{\Phi} + 2\alpha_r(\dot{\Phi} - \dot{\theta}) + \omega_r^2(\Phi - \theta) = 0 \quad (18)$$

$$\ddot{\theta} + 2\alpha_N\dot{\theta} - 2\alpha_r\frac{k^2}{l^2}(\dot{\Phi} - \dot{\theta}) + \left(\omega_N^2\theta - \omega_r^2\frac{k^2}{l^2}(\Phi - \theta) = \ddot{y}/l\right)$$

where

$$\alpha_N = q\gamma/2Ml^2$$

$$\alpha_r = q_r\gamma/2Mk^2$$

$$\omega_N^2 = \tau\gamma/Ml^2$$

$$\omega_r^2 = \tau_r\gamma/Mk^2$$

But

$$y = A \sin \omega t$$

Therefore, making the substitutions

$$Q_1e^{j\mu} = \frac{A\omega^2}{l}(\omega_r^2 - \omega^2 + 2j\alpha_r\omega)$$

$$Q_2e^{j\nu} = \frac{A\omega^2}{l}(\omega_r^2 + 2j\alpha_r\omega)$$

$$\Delta e^{j\zeta} = (\omega_r^2 - \omega^2)(\omega_N^2 - \omega^2) - \omega^2\omega_r^2k^2/l^2 - 4\alpha_N\alpha_r\omega^2 + 2j\omega[\alpha_N(\omega_r^2 - \omega^2) + \alpha_r(\omega_N^2 - \omega^2 - \omega^2k^2/l^2)]$$

it follows that

$$\left.\begin{aligned} \theta &= -\frac{Q_1}{\Delta}\sin(\omega t + \mu - \zeta) \\ \Phi &= -\frac{Q_2}{\Delta}\sin(\omega t + \nu - \zeta) \end{aligned}\right\} \quad (19)$$

The undamped natural frequencies of the damper are obtained by equating Δ, with the α-terms eliminated, to zero, i.e.,

$$f^4 - f^2(f_N^2 + f_r^2 + f_r^2k^2/l^2) + f_r^2f_N^2 = 0 \quad (20)$$

The damper is designed so that the lower natural frequency is below the range of frequencies to be suppressed, as discussed in relation to figure 3. When

the torsional resistance of the resilient material is greater than that of the conductor, the range of frequencies below the higher natural frequency of equation 20 will not be suppressed adequately if the mode of vibration about the conductor has the lower frequency. In such a case, it is necessary to decrease the frequency f_r of the mode associated with the resilient material.

The rate of energy dissipation is

$$P=\frac{1}{T}\int_0^T [q\dot{\theta}^2+q_r(\dot{\theta}-\dot{\Phi})^2]dt$$

$$=\frac{\omega^2}{2\Delta^2}[qQ_1^2+q_r\{Q_1^2+Q_2^2-2Q_1Q_2\cos(\mu-\nu)\}] \quad (21)$$

The last term approaches a maximum contribution as $(\mu-\nu)\rightarrow\pi$, and its minimum as $(\mu-\nu)\rightarrow 0$. For an undamped condition, equation 18 can be written

$$(\omega_r^2-\omega^2)\Phi=\omega_r^2\theta$$

It is evident that $\theta=-\Phi$ is possible, in this case, only at one frequency, viz., $f=\sqrt{2}f_r$. The relation $\theta=\Phi$ can exist if $f=0$ or ω_r is very large. The first condition is not satisfied; the second is present for a large τ, and the device would be a rigid damper. Consequently, the resilient joint has a dissipative effect at all operating frequencies, although it reaches a maximum displacement only at a unique frequency.

For a large mass, which is necessary to obtain the low undamped natural frequency, and a high conductor frequency, the following approximations hold:

$Q_1\rightarrow A\omega^2/l$
$Q_2\propto\omega^2$
$\Delta\rightarrow\omega^4$
$\mu\rightarrow\pi$
$\nu\rightarrow\pi/2$
$\zeta\rightarrow 0$

With these values, equations 19 and 21 become

$$\Phi\approx 0$$

$$\theta=(A/l)\sin\omega t$$

$$P=\frac{\omega^2A^2}{2l^2}(q+q_r)$$

Using the mathematical reasoning of the previous section and relation 3, it can be shown that

$$q=\delta\tau/\pi\omega$$

$$q_r=\delta_r\tau_r/\pi\omega$$

Physical Constants

The logarithmic decrement and angular elastic constant are required for numerical computations and can be found experimentally, in one way, from the decrement curves of free torsional motion.

To illustrate the magnitude of these quantities: For a 795,000 cir-mil ACSR, $\delta\approx 0.19$ and τ per foot varies from 230 lb.-ft./rad. at 3,000 pounds tension to 360 lb.-ft./rad. at 5,700 pounds tension. For a 336,000 cir-mil ACSR, $\delta\approx 0.20$ and τ per foot is 46 lb.-ft./rad. at 1,200 pounds tension increasing to a constant value of 78 lb.-ft./rad. at approximately 3,600 pounds tension.

Summary

In the theoretical treatment of the torsional damper, the following conclusions pertaining to the general design of dampers have been deduced:

1. The angular elastic constant and, thus, the torsional resistance are inversely proportional to the length of effective conductor.

2. The undamped natural frequency of the damping system has to be below the lowest prevalent conductor frequency to be suppressed.

3. The damper is placed at the point of highest amplitude, consistent with maintaining a low natural frequency and a high torsional resistance. The effect of amplitude variations over the frequency band on the determination of spacing is not very critical, because the damper has to be effective over such a large range of loop lengths (possibly 5 to 50 feet).

4. For a rigid damper, the distance from the centre of the conductor to the centre of gravity should be as short as possible and equal to the radius of gyration about the centre of gravity. The damper, applied singly, should be placed near the clamp and still satisfy conclusions 2 and 3.

5. With the arrangement of figure 4, the two rigid dampers are mounted in the same loop in order to take advantage of the mutual dissipation. The optimum spacings, which will be short for large torsional resistances, could be determined by calculation for specific cases.

6. The single damper with a resilient joint is required for conductors having a small damping capacity. This type of damper has an advantage over the rigid type in that the damping factor of the resilient material can be varied, whereas that of the conductor is fixed. The spacing for this device is found in the same manner as for the rigid damper. As an example, the torsional damper of figure 1 is installed 6 feet from the clamp on 795,000 cir-mil ACSR.

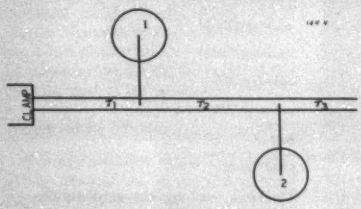

Figure 4. Schematic arrangement of two rigid dampers at one end of a span (horizontal plane)

Appendix

The rigid analysis of the motion of a single rigid damper will be developed to show that the above solutions are approximations strictly valid for short spans.

The torsional wave equation

$$\frac{\partial^2\theta}{\partial t^2}=a^2\frac{\partial^2\theta}{\partial x^2}$$

in which

$a^2=Gg/\gamma$ = velocity of propagation squared
G = modulus of rigidity
γ = weight per unit volume

has a solution of the form

$$\theta=X\sin\omega t$$

Let one end of a span of length s be the origin and the damper be placed a distance b from the origin. For the end conditions

$\theta=0$ at $x=0$ and $x=s$,

the space function can be written

$$X_1=C\sin\frac{\omega x}{a}: \qquad 0\geq x\geq b$$

$$X_2=D\sin\frac{\omega(x-s)}{a}: \quad b\geq x\geq s$$

The conditions to be satisfied at $x=b$, with I_p representing the moment of inertia of the area of cross section of the conductor, are

$$\left.\begin{aligned}&\theta_1=\theta_2\\ &I\frac{\partial^2\theta_1}{\partial t^2}=-GI_p\left[\frac{\partial\theta_1}{\partial x}-\frac{\partial\theta_2}{\partial x}\right]\end{aligned}\right\} \quad (22)$$

Eliminating C and D, the natural frequencies are given by

$$\tan\frac{\omega(b-s)}{a}\left[\tau'\cot\frac{\omega b}{a}-a\omega I\right]=\tau'$$

where

$\tau'=GI_p$

For a practical installation, $s\gg b$ and b is small. Then, with $\beta=\omega s/a$,

$$\tan\beta=\frac{\tau' b\beta}{\beta^2a^2bI/s-\tau's} \quad (23)$$

having consecutive roots $\beta_i(i=1, 2, 3\ldots)$.

When β has a value such that tan $\beta \rightarrow \beta$, the natural frequency becomes

$$\omega_c^2 = \tau'/bI \qquad (24)$$

which agrees with the approximate theory.

For forced oscillations, the solution in generalized co-ordinates is

$$\theta_1 = \sum_{i=1}^{i=\infty} x_i \sin \frac{\beta_i x}{s} : \qquad 0 \geq x \geq b$$

$$\theta_2 = \sum_{i=1}^{i=\infty} x_i \left(\frac{D}{C}\right)_{\substack{\beta=\beta_i \\ x=b}} \sin \frac{\beta_i (x-s)}{s} : b \geq x \geq s$$

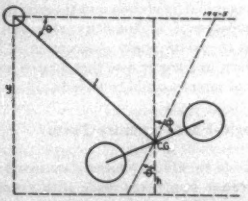

Figure 5. Schematic diagram of a damper with a resilient joint at the center of gravity

The potential energy function is

$$V = \frac{\tau'}{2}\left[\int_0^b \left(\frac{\partial \theta_1}{\partial x}\right)^2 dx + \int_b^s \left(\frac{\partial \theta_2}{\partial x}\right)^2 dx\right]$$

$$= \tau' \beta_i (A_i + B_i) x_i^2 / 8 s^2$$

with

$$A_i = 2\beta_i \left[b - (b-s)\left(\frac{D}{C}\right)^2_{\substack{\beta=\beta_i \\ x=b}}\right]$$

$$B_i = s\left[\sin \frac{2\beta_i b}{s} - \left(\frac{D}{C}\right)^2_{\substack{\beta=\beta_i \\ x=b}} \sin \frac{2\beta_i (b-s)}{s}\right]$$

The kinetic energy function is

$$S = \frac{\gamma I_p}{2g}\left[\int_0^b \left(\frac{\partial \theta_1}{\partial t}\right)^2 dx + \int_b^s \left(\frac{\partial \theta_2}{\partial t}\right)^2 dx\right] +$$

$$\frac{I_g}{2}\dot{\theta}_{x=b}^2 + \frac{M}{2g}(\dot{y} - l\dot{\theta})_{x=b}^2 =$$

$$= \left[\frac{\gamma I_p (A_i - B_i)}{8 g \beta_i} + \frac{I_g}{2}\sin^2 \frac{\beta_i b}{s}\right]\dot{x}_i^2 +$$

$$\frac{M}{2g}\left(\dot{y} - l\dot{x}_i \sin \frac{\beta_i b}{s}\right)^2$$

Applying Lagrange's equation, the differential equation for x_i is:

$$\left[\frac{\gamma I_p (A_i - B_i)}{4 g \beta_i I} + \sin^2 \frac{\beta_i b}{s}\right]\ddot{x}_i +$$

$$\frac{\tau' \beta_i (A_i + B_i)}{4 I_g^2} x_i = \frac{l\ddot{y}}{K^2} \sin \frac{\beta_i b}{s}$$

For the condition tan $\beta \rightarrow \beta$

$$A_i \rightarrow B_i \rightarrow 2\beta_i b$$

and the differential equation simplifies to

$$\left(\sin \frac{\beta_i b}{s}\right)(\ddot{x}_c + \omega_c^2 x_c) = l\ddot{y}/K^2$$

Hence, for $K \rightarrow l$ and $\omega \gg \omega_c$

$$\theta_{x=b} = (A/l) \sin \omega t$$

The general solution of torsional dampers with the damping constants is obviously complex. The single natural frequency of the approximate solution is replaced by a series of frequencies in the general solution of a long span, since the distributed mechanical system of the conductor becomes a major part of the vibratory system. However, the lowest natural frequency of equation 23 is less than that of equation 24 for long spans and a damper designed for the approximate conditions will be effective when tan $\beta \neq \beta$.

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The Protection of Solid Insulation by Lightning Arresters

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Introduction

THE protection of distribution transformers or other apparatus against lightning involves the basic problem of limiting the voltage applied to the insulation to a value adequately below the insulation strength. The effect on insulation of chopped waves and full waves of standard impulse wave shapes such as 1.5x40 microseconds has been thoroughly investigated in the past. However, there has been a lack of the information necessary to compare the effect of chopped waves with the effect of voltages of other than standard wave shape resulting from arrester breakdown followed by the impedance drop that occurs during the impulse current discharge. Also there have been little data available on the failure of low voltage insulation. For these reasons an investigation has been made using oil immersed solid insulation of a type used in distribution transformers. The puncture voltage and number of shots to failure were determined when the insulation was in parallel with lightning arresters or gaps which controlled the wave shape of the voltage applied to the insulation. These results have been correlated with the single shot puncture voltage determined from tests in which failure occurred on the wave front. It was found that repeated applications of voltages in excess of approximately 70 per cent of the single shot puncture voltage may damage the insulation.

Insulation Samples

The insulation tested consisted of pads of 10- by 10-inch sheets of kraft paper 5 mils in thickness. Thin sheets of paper were used so that the failure voltage could be varied in small steps by changing the number of sheets in series. The line electrodes were pancake coils 2 inches in outer diameter and 1 inch in inner diameter wound from 85- by 155-mil copper, see figure 1. The turns of the line electrodes were wrapped with paper insulation of a type used in transformers. This insulation raised the corona voltage and made the failure voltage of the insulation pads less erratic. The turns of the coils were tied with 15-mil thread since thread and tape are sometimes used on transformer coils. The maximum thickness of the coil insulation at points of contact with the paper was about 20 mils but was variable due to the thread and the paper wrapping. At the ends of the coil, the copper strips were bent perpendicular to the plane of the coil and brought up through a 15-lb cylindrical weight 2 inches in outside diameter used to assure good contact. These leads were connected in parallel to the impulse generator. The pads were immersed in transformer oil in a metal tray that served as the ground electrode. Both the coils and the paper were vacuum treated and oil impregnated before the tests to eliminate moisture and absorbed air. The samples were kept under oil at all times until failure. Although all of the materials in the pads are used for certain types of insulation in transformers, the pads as tested cannot be considered[1] as representing the actual insulation strength of transformers, since in transformers steep impulse waves may result in an unequal distribution of voltage along the turns and the major insulation does not consist of paper sheets alone. In designing the insulation test pieces, it was necessary to consider the requirement of simulating transformer insulation and the additional requirements of simplicity of construction to permit ready observation of the failure, and low cost so that a large number of samples could be tested.

Figure 1. Insulation sample after puncture

A line electrode turned on edge to expose puncture and a small section of the sheet of 10- by 10-inch kraft paper used are shown. The bottom of an oil-filled metal tray formed the ground electrode

Single-Shot Puncture Tests

Tests in which puncture occurred on the wave front were made with impulse voltages of negative polarity that rose at a uniform rate until chopped by insulation puncture. A new line electrode and new sheets of paper were used for each test. The puncture voltage and time were determined, by means of cathode ray oscillograms, see figure 2, for line electrodes alone and line electrodes in series with pads of two, five, and eight sheets of paper. As the thickness of the insulation pads was changed the constants of the impulse generator circuit were adjusted so as to produce puncture at approximately the desired time. In those cases where the wave initially departed from a uniform rate of rise, the virtual zero was determined by a chord through the 30 and 90 per cent points on the voltage oscillogram. The results are plotted in figure 3. The failure in all cases was due to puncture through the paper and tended to occur near the outside of the line electrodes; corona was observed during tests of pads with five and eight sheets of paper.

Since it is desirable to base average curves on all of the available test data, the test results were correlated by means of figure 4 in which the average puncture voltage for failure times of 0.2, 1, and 8 microseconds was plotted against the paper thickness. The solid line curves of figure 3 give the puncture voltage from tests on line electrodes alone and pads with two, five, and eight sheets of paper; all of the original data points were plotted. The broken line curves for three, four, six, and seven sheets were obtained by interpolation from figure 4.

From figure 3 the puncture voltage at

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1. For all numbered references, see list at end of paper.

0.25 microsecond is about 116 per cent of the value at 1 microsecond. Tests by Montsinger[1] gave a ratio of 160 per cent for the failure voltages at the same value of time. It is suggested that this difference is due to the considerable differences in the structure of the insulation samples tested in the two investigations and to differences in the applied voltage waves. Montsinger's tests were made on insulation barriers 0.64 and 2.5 inches in total thickness with relatively large oil ducts; the samples were designed to simulate the major insulation used in high voltage transformers.

From figure 4, it is evident that the average puncture voltage increased linearly with the total thickness of the paper sheets in the pad. This is evidence that the strength of the individual paper sheets and the distribution of voltage were uniform. Although the line electrode insulation measured 20 mils in thickness including the thread, it had a puncture voltage equivalent to 7.5 mils of the 5-mil paper. Failure tended to occur at the threads presumably due to a concentration of stress.

Puncture of Insulation in Parallel With Arresters or Gaps

A second series of tests was made with pads in parallel with 9-kv distribution arresters or gaps set for values of impulse breakdown within the range permitted by lightning protective devices used on 6,900-volt circuits. Several types of gaps were used among which were $^1/_2$-inch square rod gap set at $^{61}/_{64}$ inch and $2^1/_{16}$ inches; and sphere gaps 6.25 centimeters in diameter set at 16 millimeters. Cathode ray oscillograms were taken to show the failure voltage and time, see figure 5. A new line electrode and new sheets of paper were used for each test but not for each impulse. Although the applied impulse voltage wave was changed during the series of tests, each individual sample was punctured by repeated applications of the same voltage wave except that the tests were stopped in three cases after 100 or more shots. A total of 95 pads was tested and the results are summarized in the tabulation. In all tests the applied voltage rose at an approximate rate of 500 kv per microsecond until reduced by the arrester or gap or by puncture of the insulation. The rate of 500 kv per microsecond exceeds the rate of 100 kv per microsecond recommended in the appendix to "Standards for Testing Lightning Arresters," ASA C-62, and is perhaps representative of the steeper rates to which distribution arresters in service are subjected. The gap and arrester breakdown voltages in the tabulation exceed the values obtained from tests with voltages rising at 100 kv per microsecond. For example the 9-kv valve type arresters have a breakdown voltage of approximately 50 kv on the 100 kv per microsecond tests whereas a breakdown of 69 kv is given in the table for the 500 kv per microsecond wave. The time to breakdown of the arresters or gaps ranged from 0.13 to 0.30 microsecond on the 500 kv per microsecond wave. These values of time to breakdown of the arresters or gaps are small compared to the range of one to four microseconds required for the *IR* voltage to reach crest and are still smaller in comparison with the duration of the *IR* voltages produced by current discharges that decayed to half value in 40 microseconds.

Figure 2. Volt-time oscillogram taken during single-shot puncture tests on eight sheets of 0.005- by 10- by 10-inch paper

When arresters were used, the impulse current had a crest of 5,000 amperes, an initial rate of 2,200 amperes per microsecond, and a time to half value of 40 microseconds. The value of 5,000 amperes crest was chosen for the current since 88 per cent of the discharge currents measured[2] through rural distribution arresters in service did not exceed this value. While comparatively little information is available[3] on rates of rise and duration of currents discharged by arresters in service, it is believed that the impulse discharge used in these tests was of more than average severity.

When gaps were tested, the impulse discharge current crest was 500 amperes or less and the time to half value was 40 microseconds. The value of approximately 500 amperes was selected for the magnitude of the discharge current as a matter of convenience and to give arc voltages and inductive drops that were small. For part of the tests, wire-wound resistors of 120 to 150 ohms were connected in series with the gaps to study the effect of *IR* voltage on insulation failure. Cathode ray oscillograms, see figure 5, showed whether the insulation failure occurred as the voltage was rising to gap breakdown or during the subsequent application of *IR* voltage to the insulation.

Comparison of Test With and Without IR Voltage

By means of the data in the tabulation, it is possible to compare the effect on insulation failure of breakdown voltage without subsequent *IR* voltage, with the effect of breakdown voltage followed by *IR* voltage. The per cent of single shot puncture voltage given in the tabulation is the ratio of the breakdown or *IR* voltage applied to the pad to the average single shot voltage determined from figure 3 for a pad with the same number of sheets. When valve arresters were tested the crest *IR* voltage occurred at one to two microseconds so the single shot puncture voltage curves were read at 1.5 microseconds; the wire-wound resistors gave crest *IR* voltages at two to four microseconds, and the curves were read at 3.0 microseconds. In tests 1 and 2 with valve type arresters puncture always occurred as the voltage was rising to gap breakdown; two-sheet pads failed in 1 to 5 shots and three-sheet pads in 3 to 14 shots. In test 3 with gaps set for

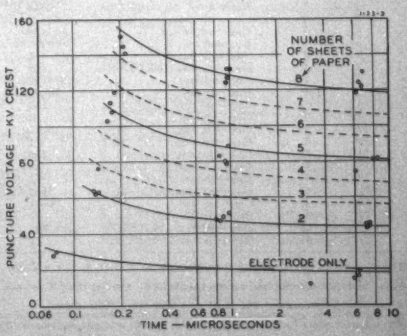

Figure 3. Volt-time curves for single-shot puncture from front-of-wave tests

The solid lines are the average volt-time curves from the original data as correlated by figure 4. All original data are plotted

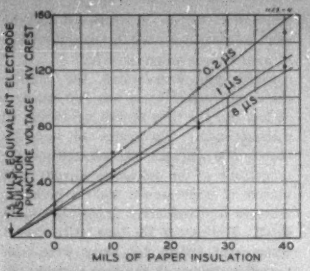

Figure 4. Average single-shot puncture voltage from front-of-wave tests

nearly the same impulse breakdown as in tests 1 and 2 but having no *IR* drop, two-sheet pads failed in one shot. In test 4, six of the three-sheet pads failed in one to nine shots (see footnote in tabulation) and the seventh pad withstood an abnormal number of shots. A comparison of tests 1 and 2 with tests 3 and 4 shows that valve arrester *IR* drops of 74 and 58 per cent of the average single shot puncture voltage did not reduce the number of shots required to fail the insulation.

However, it is evident that the *IR* voltage if sufficiently high will reduce the number of shots the insulation can withstand. This is seen from tests 4, 5, and 6 and tests 7, 8, and 9. The gap breakdown voltage was approximately equal for the three tests 4, 5, and 6. Test 4 was made with no *IR* voltage. In test 5 the *IR* voltage was 84 per cent of the single shot strength and puncture occurred on the *IR* voltage in two out of the seven tests. In test 6 with an *IR* voltage of 95 per cent of the single shot strength, puncture always occurred on the first shot during the *IR* voltage. These tests indicate that repeated shots with *IR* voltages in excess of 84 per cent of the single shot strength will deteriorate the insulation.

The three tests 7, 8, and 9 were all made with the same gap and give additional information on the effect of *IR* voltage. In test 7 there was no *IR* voltage and two pads each withstood 102 shots. In test 8 the *IR* voltage was 69 per cent of the single shot failure voltage and three of the pads tested punctured on shots 25, 34, and 86 while the fourth pad withstood 109 shots without failure. Although it might be inferred from a comparison of tests 7 and 8 that the *IR* voltage reduced the number of shots to fail the insulation, the number of pads are so few in test 7 and the range of shots so large in test 8 that such a deduction is questionable. On test 9 the *IR* voltage was 78 per cent of the single shot puncture voltage and failure occurred in fewer shots than in tests 7 and 8.

The remainder of the tabulation shows the number of shots required to puncture pads with various amounts of insulation when the voltage was chopped by gaps without series resistance. The protective ability of these gaps was approximately equivalent to a rod gap set two inches, since the breakdown voltages ranged from 112 to 125 kv and there was

Figure 5. Volt-time oscillogram taken on pad with three sheets of paper

The pad was protected by 6.25-centimeter spheres set 16 millimeters with a resistance of 150 ohms connected in series. Puncture occurred during the *IR* voltage at about 1.7 microseconds. This oscillogram was retouched for reproduction

no *IR* voltage. With these gaps in parallel with the pads, it was necessary to have from five to eight sheets in the pads to withstand the same number of shots as were withstood by pads with two or three sheets when tested in parallel with valve arresters that had a breakdown voltage of 69 kv and an *IR* voltage of 34-kv crest.

Effect of Repeated Shots on Insulation Puncture

Thus far comparisons have been made between part of the individual tests listed in the tabulation. However, the effect of repeated shots can best be determined by putting the data from all tests on a common basis. This has been done in figure

Tests on Insulation Pads in Parallel With Gaps and Arresters

Test Number	No. of Sheets in Pads	Voltage Limited by	No. of Pads Tested	No. of Shots to Fail Pad	Pad Failed During	Average Voltage Applied—Kv Crest: Bkd. at 500 Kv/μs Bkd.	Average Voltage Applied—Kv Crest: 40 μs to Half-Current IR	Average Single Shot Strength, Figure 3—Kv Crest: Bkd.	Average Single Shot Strength, Figure 3—Kv Crest: IR	Ratio of Average Applied Voltage to Average Single Shot Strength—Per Cent: Bkd.	Ratio of Average Applied Voltage to Average Single Shot Strength—Per Cent: IR
1	2	Valve arr.	7	1–5	Breakdown	69	34	63	46	109	74
2	3	Valve arr.	8	3–14	Breakdown	69	34	80	59	86	58
3	2	Gap—no res.	4	1	Breakdown	69	0	64	0	108	
4	3	Gap—no res.	7	1–78[a]	Breakdown	72	0	78	0	92	
5	3	Gap and res.	7	1–2[b]	Bkd. or *IR*	79	49	77	58	103	84
6	3	Gap and res.	5	1	*IR*	70	55	80	58	88	95
7	4	Gap—no res.	2	102[c]		69	0	99	0	70	
8	4	Gap and res.	4	25–109[d]	Breakdown	69	48	99	70	70	69
9	4	Gap and res.	2	23, 27	Unknown	69	55	99	71	70	78
10	5	Gap—no res.	6	1–4	Breakdown	112	0	105	0	107	
11	6	Gap—no res.	2	3	Breakdown	112	0	120	0	93	
12	7	Gap—no res.	6	5–12	Breakdown	113	0	139	0	81	
13	5	Gap—no res.	6	1	Breakdown	112	0	105	0	107	
14	7	Gap—no res.	6	2–9	Breakdown	113	0	136	0	83	
15	8	Gap—no res.	1	25	Breakdown	115	0	133	0	86	
16	5	Gap—no res.	1	1	Breakdown	117	0	107	0	109	
17	6	Gap—no res.	5	1–2	Breakdown	119	0	119	0	100	
18	8	Gap—no res.	7	4–12	Breakdown	125	0	148	0	84	
19	6	Gap—no res.	4	1	Breakdown	118	0	119	0	99	
20	8	Gap—no res.	4	3–5	Breakdown	124	0	150	0	83	
21	9	Gap—no res.	1	12	Breakdown	120	0	165	0	73	

NOTES: [a]Number of shots to puncture pads: 1, 1, 1, 2, 4, 9, and 78.

[b]Five pads were punctured on the breakdown; two on the *IR* voltage.

[c]Two samples withstood 102 shots and tests were discontinued.

[d]Number of shots to puncture pads: 25, 34, 86, and one withstood 109 shots.

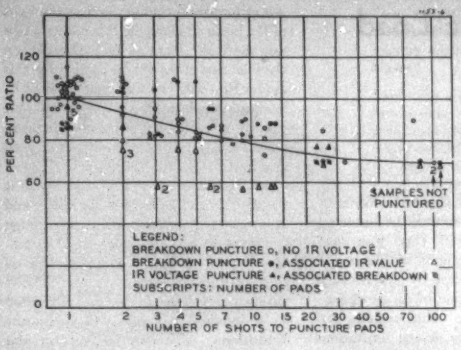

Figure 6. Tests with repeated shots

The applied voltage, in per cent of the single-shot puncture voltage, is plotted against the number of shots to puncture the pads. The insulation pads were in parallel with gaps or arresters

6 where the applied voltage expressed in per cent of the single shot puncture voltage was plotted against the number of shots to rupture the insulation. Data points were plotted from each of the 95 pads tested whereas the tabulation was condensed to include only averages or the ranges of data. A point was plotted for arrester or gap breakdown voltage and another for the *IR* voltage when it existed. The symbols indicate whether the puncture occurred as the voltage rose to gap breakdown or during the subsequent *IR* voltage. Since a large number of insulation punctures occurred on the first few shots, these points have been grouped about the ordinate through the actual shot number. Factors responsible for the scattering of the points include variations in the gap or arrester breakdown voltages, variations in the impulse generator discharge from shot to shot, and variations in the puncture voltage of individual pads.

The curve in figure 6 shows that the number of shots required to fail the insulation increases as the applied voltage expressed in per cent of the single shot puncture voltage is reduced. In all tests in which the insulation was ruptured, either the breakdown or the *IR* voltage was at least 70 per cent of the single shot puncture voltage. It is concluded from this plot that the insulation will withstand a large number of repeated shots provided the applied voltage does not exceed a value of approximately 70 per cent of the single shot puncture strength at any value of time. Within the limits of this investigation, this conclusion holds irrespective of whether the applied voltage is of short or long duration. On the basis that the curves of figure 3 are 100 per cent, it is concluded that curves drawn through 70 per cent of the voltage will approximate the shape of the highest voltage wave that can be repeatedly applied without reducing the number of shots the insulation will withstand. Montsinger[1] found that repeated shot injurious corona appears at voltages of 65 to 90 per cent of the single shot failure voltage and concluded that 80 per cent is a safe average value of voltage for repeated shots. The value of 70 per cent from the present tests is in good agreement with his results notwithstanding the differences in the structure of the insulation tested in the two investigations.

The Effect of Voltage Wave Shape on Insulation Puncture

One object of this investigation was to determine if arrester *IR* voltages of relatively low magnitude might possibly be more destructive to insulation because of long duration than voltages of relatively short duration preceding the breakdown of gaps. This was not found to be the case in these tests. The higher voltages necessary to puncture the insulation samples at short values of time are due to turn up of the insulation volt-time characteristic. Although figure 3 shows that higher voltages are required to cause puncture in short values of time, this might be offset in transformers by nonuniformity in distribution of voltage between the turns of the transformer coils which increases with the steepness of the voltage applied. Although these tests on insulation samples showed no evidence of deterioration of the insulation due to voltages less than 70 per cent of the single shot strength, the conclusion should not be drawn that chopped waves of this magnitude are necessarily harmless to turn insulation in actual transformers.

Conclusions

(1). The single shot puncture of the insulation increased linearly with the insulation thickness over the range tested in this investigation.

(2). The single shot volt-time puncture curves of the insulation tested in this investigation are relatively flat; the average puncture voltage for failure at 0.25 microsecond was found to be only 16 per cent more than the puncture voltage at 1 microsecond.

(3). This investigation shows that valve type arresters, of the type tested and the rating applied on 6,900-volt circuits, are superior to two-inch rod gaps for the protection of insulation when subjected to impulse discharges that are of more than average severity based upon field records.

(4). Tests with repeated applications of impulse voltages showed that as the ratio of the applied voltage to the single shot puncture voltage is reduced, the number of shots necessary to rupture the insulation increases.

(5). The insulation tested withstood a relatively large number of shots provided the applied voltage did not exceed a value of approximately 70 per cent of the single shot puncture voltage at any instant of time during the application.

(6). From life tests during which the insulation was subjected to voltage waves modified by the operation of protective devices, it is concluded that the insulation will withstand a relatively large number of shots provided the instantaneous voltage due to breakdown or *IR* voltages does not exceed approximately 70 per cent of the single shot puncture voltage.

(7). The results of this investigation suggest that in the application of protective devices, the upper limit of the stress that can be safely applied repeatedly to new insulation may be regarded as 70 per cent of the single shot puncture voltage; this is irrespective of whether the highest stress permitted by the protective devices is due to short or long time gap breakdown or short or long duration *IR* voltages.

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A New Transformer for Base-Load Stations

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Synopsis: This paper describes the application of Hipersil to three 40,000 Kv-a units for the Philo generating station of The Ohio Power Company. Because of Hipersil's ability to carry one-third more magnetic flux, appreciable savings in weight and dimensions are possible—in fact, the transformers will be shipped in oil completely assembled with bushings in place, ready to operate.

Forced-oil and forced-air cooling are provided, with proper relays for protection in the event of excessive copper temperature or failure of auxiliaries. Reliability, economy, ease of installation, and low maintenance have been the objectives sought in the design.

ALTHOUGH technical progress in the art of transmission of electrical energy has been considerable in the last two decades, it is a fact that no single significant contribution looking toward more economical transmission is readily called to mind. Most particularly is this true in the case of the transformer—the essential link in a-c transmission. Thus, major design and construction improvements have been made in impulse strength, in lightning protection, and in impulse testing of transformers. But these developments have only indirectly affected cost. Even more notable is the fact that a design trend of many years background in the direction of continually reducing losses has not been re-examined, nor most certainly altered in the face of decreasing costs of electrical capacity and energy. The development described here, it is believed, marks a definite step in altering that condition.

The essential element in this new design is a new steel, Hipersil.[1] Its outstanding characteristic is its ability to carry approximately one-third more magnetic flux in the transformer core. Figure 3 shows equipment used in a test made on two model cores identical in size—one of silicon steel and one of Hipersil. With the same exciting ampere-turns the flux measured in the Hipersil core was 38% greater than in the silicon steel core. It is hoped at a later date to present some more extensive information on the characteristics of Hipersil. This pushing forward of some of the design limitations which have heretofore held in check transformer designers, even though, for the present at least, the advantages of the new material must be limited to transformers where it can be used with the magnetic flux in line with the direction of rolling, is bound by itself to have a most material effect on transformer design economics and on transformer design art. In the development described, Hipersil has been coupled with forced-oil cooling, and with re-examined criteria for losses in the light of modern power and energy economics. But safety and reliability, as will be evident from the more detailed description to follow, have not been sacrificed.

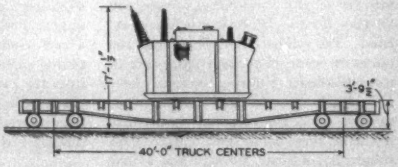

Figure 1. 40,000-kva 138-kv transformer mounted on standard flat car for shipment

In spite of the large size of this transformer, it will be shipped completely assembled with cooling equipment, oil bushings, and lightning arresters in place

Description of Transformer Units

This paper presents specifically the results of an analysis to see what the possibilities of this new material and new ideas would be in the design of large transformers for a base load station. The particular units under consideration are rated 40,000 Kv-a, 138 Kv, with non-solidly grounded neutral. The relatively lower cost of energy at the station bus was fully considered in evaluating the transformer losses and it made possible a closer use to the full of the inherent properties of Hipersil in reducing dimensions and the amount of active material required.

It was found that the smaller weights and dimensions resulting from the greater flux carrying capacity of Hipersil could be reduced still further through the use of forced-oil cooling, and in the light of the basic aim sought, this construction was adopted. Another factor bearing on the selection of forced-oil cooling for this application was the fact that little overload capacity is needed in a base load unit operating on the unit principle with generator and transformer in series switched as a unit.

As a result of these two basic ideas it was found possible to reduce weights and dimensions to a point where these large transformers could be completely assembled in the factory to be shipped in oil with bushings in place. Figure 1 shows an elevation of one of these units mounted on a standard flat car with significant dimensions. The cost of erection and starting in the field will obviously be reduced to a minimum.

Another interesting feature of these transformers is that due to the small size and the relatively small amount of oil involved it was possible to weld the cover on and seal the unit permanently against deterioration of the oil and insulation. There is no provision for breathing.

When operating at full load, these transformers have oil circulating pumps and fans in continuous operation, but much thought has been given to the question of reliability and protective devices. It is believed that with the arrangements described below, a degree of reliability comparable with that of other major apparatus in the generating station has been obtained.

It is interesting to examine the reduction in weights and increase in losses of this transformer compared with a standard self-cooled air-blast unit of the same rating:

Copper windings	reduction in weight 10%
Core	reduction in weight 25%
Losses	increase in weight 5%

Cooling System

The transformer itself is of shell-type construction and is mounted horizontally in the tank. Fin-type coolers employing round tubes of substantial cross-section are mounted on each side of the tank wall and provided with circulating pumps and cooling fans. The two radiator assem-

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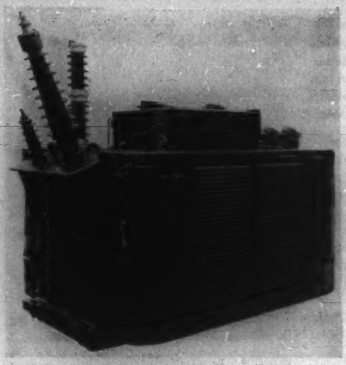
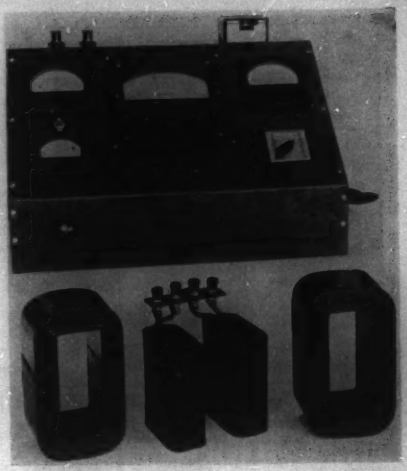


Figure 2. Side elevation of 40,000-kva 138-kv transformer showing principal over-all dimensions

The transformer is completely sealed with cover welded in place. No auxiliary gas equipment is required since adequate gas space is provided in the tank for maximum expansion and contraction due to temperature changes

Figure 3 (right). Test to demonstrate flux-carrying capacity of Hipersil

Two cores identical in size—one silicon steel, one Hipersil—were excited with 0.5 ampere through a coil of 154 turns. The voltage across the coil when assembled on the silicon steel core was 92—when on the Hipersil core, 127. Since the flux produced in the core is proportional to the voltage, the Hipersil core carried a flux greater than the silicon steel, in the ratio of 127 to 92, or approximately 38 per cent greater



blies are operated as independent units. Power for the pumps and fans is supplied from two auxiliary transformers mounted inside the main unit—one auxiliary transformer taking care of one radiator bank. However, each of these auxiliary transformers is of sufficient capacity to supply power for the pumps and fans of both cooling units, and the control is so arranged that in the event one auxiliary transformer should fail, its fans and pump can be immediately connected to the other transformer. The control, too, is so arranged that both oil circulating pumps operate at no load but the fans come on as required; that is, when the oil temperature reaches 65°C, one set of fans comes into operation; at 75°C, the second set of fans comes into play.

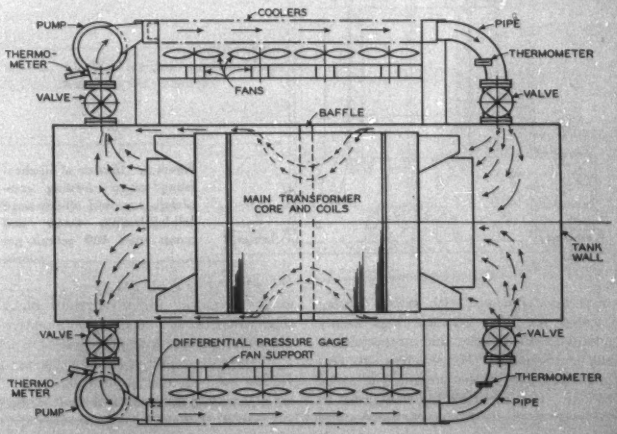
Differential pressure relays are provided on each circulating pump. With only one pump in operation the capacity of the transformer would be reduced to 80%. Should the oil flow stop through one of the coolers due to failure of the pump or any other cause, the differential pressure relay would sound a warning to the station operator. Should both pumps stop, a signal to clear the unit from the line is given.

Operation by Copper Temperature

Since the thermal capacity of these transformers is small—comparatively little oil being required—excess copper temperatures could be reached in a relatively short time in the event difficulty should develop in the cooling system. For this reason relays are provided in each unit which operate on copper temperature. At 105 degrees centigrade copper temperature (measured by resistance), a warning signal is sounded to the station operator indicating that steps should be taken to reduce the load. It is not likely that the transformers would be actually overloaded due to the limitation of the generating equipment in the station, but it is conceivable that in the event of failure of fans or pumps on one side of the unit, even normal full load would exceed its reduced load carrying capacity. Should the copper temperature continue to increase and reach a dangerous point, the copper temperature relay signals the station operator for immediate shut-down.

Figure 4. Plan view showing oil circulation system

Pumps and fans are arranged in two independent assemblies each supplied from a separate auxiliary transformer mounted inside the main tank. Protection to the unit is provided in the event of failure of pumps by means of differential pressure relays and in the event of fan failure by copper temperature relays



Fans and Pumps

A number of different blower arrangements were attempted during the course of the design but the use of simple air-

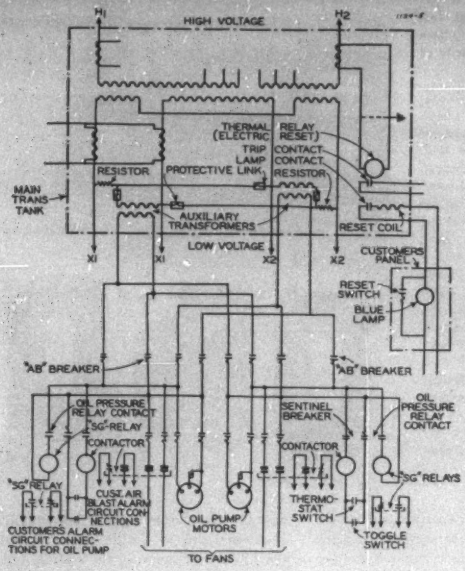


Figure 5. Schematic diagram showing arrangement of control apparatus mounted in control cabinets on transformer

Auxiliary transformers mounted inside main unit are provided with protective links to clear circuit in case of winding failures. Either auxiliary transformer will supply all pumps and fans by closing proper *AB* breakers. Fans are controlled from thermostatic relays operating on oil temperature. Pump motors run continuously. Copper-temperature relay protects against excessive copper temperature in the event of overload or failure of auxiliaries

Figure 7. Bird-wing fan mounted in removable assemblies of four units behind radiator coolers

Motors are outdoor capacitor-type equipped with "sealed-for-life" bearings. Capacitors are mounted in control cabinets on the transformer

which is completely sealed and mounted in the oil circulation system so that both stator and rotor windings are submerged and bearings continually lubricated at all times by the transformer oil itself. Consideration has also been given to the problem of changing the pump motor and impeller assembly in the shortest possible time should that ever become necessary.

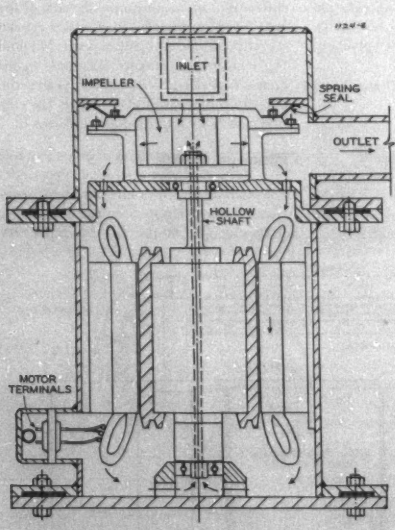


Figure 6. Section of oil circulating pump showing completely enclosed oil-immersed self-lubricating motor and pump rated 400 gallons per minute

Conclusions

The development of Hipersil has opened up many new avenues for the design of transformers. As shown here, its use, coupled with other design ideas, has made possible production of large units more economically through reduction in size and amount of material required. Weights and dimensions become particularly important in very large units. Using standard magnetic steel these have had to be shipped in nitrogen gas in special containers to get by bridge and tunnel clearances. Upon arrival they required a considerable amount of erection work and expense prior to being placed in service. The use of Hipersil automatically extends the rating size before this becomes necessary. It is apparent, too, that the same development will make possible the extending of the practical size of the portable transformer whether on car or trailer. Finally, the authors believe that this development is but another proof of the vitality of the electric power art and of the ability of modern technology to move rapidly forward even in a well developed field.

blast fans equipped with motors having "sealed for life" bearings was finally adopted as the simplest and most economical arrangement. Sixteen fans are employed on each cooler, mounted in racks of four. Consideration has been given to easy replacement of these individual racks should that become necessary as a matter of routine maintenance.

The circulator pumps are of a type previously used for this application. They are equipped with a vertical shaft motor

The Measurement of Body Currents

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NONMEMBER AIEE

IN these days of supersensitive amplifiers and recording apparatus, it is very tempting to define life and death in terms of electrical activity. Whether or not this concept is accurate, we can, on present knowledge liken living tissue to a B-battery and dead tissue to a burned out generator. The function of living tissue, however, is so closely allied with its electrical activity that knowledge of the latter has given us better understanding of the working of the human body.

Great names in electrical engineering contributed to our knowledge of the physiology of tissues. Galvani in 1780 made the really startling observation that the muscle of a frog's leg could be made to contract when stimulated with the voltage from the crude Voltaic pile. That the muscle itself, on contracting, gave off a charge of its own was shown in 1870 by D'Arsonval, who noted the deflection of the needle when the muscle contracted across the poles of his galvanometer.

With improvements and greater sensitivity in recording instruments, electrical waves were obtained from the human heart (Waller, 1885; Einthoven, 1903) and from the nerve and muscle (Lucus, 1906; and Piper). In 1929 Hans Berger, with string galvanometer and amplifiers, picked up the first electrical waves from the human brain with electrodes on the scalp.

The first type of body currents to be discussed here is the rather static, direct current potential difference. It is this ever-present E.M.F., found in all living matter, small (few millionths of a volt), but constant as to polarity and relatively unchanging in time or species, that brings up the easy analogy of life to the B-battery. The living cell shows a tiny potential difference between its surface and the centrally located nucleus (Freeman). In plants, we can find a few microvolts of D.C. potential and in one animal, the electric eel, we may find as much as 500 volts. There is strong evidence that these potentials are due to different metabolic rates or energy levels in different parts of the same structure. Thus the relatively inactive, transparent membrane covering the human eye-ball (cornea) is nearly a millivolt different from the highly active, photo-sensitive retina at the back of the eye.

Nearly anywhere in the body, such potential differences may be found and in some cases might be clinically useful. For example, if an electrode is placed in the vagina, and another on the surface of the skin of the abdomen, a sudden increase in the base-line voltage difference is said to indicate that ovulation is occurring in the underlying ovary. These D.C. potentials are always associated with the first and most important character of life, namely: absorbing energy, growth, and change in structure. We call these activities metabolism and catabolism. They are found, for example, in the rose from seed to death, although the flower never moves in the sense that animals swim, fly, walk, etc. The more active part metabolically speaking is negative to the less active part. Thus the former is essentially the −; zinc, or cathode of a battery and the less active tissue the +; carbon, or anode pole.

The second type of body currents is that associated only with the animal kingdom—the electrical activity of locomotion. It is nature's second and perhaps most interesting attribute of life, and is different from any of the D.C. potentials previously described. Contractile tissue is nature's first intrinsic movement in an environment of physical forces all in motion, such as wind, tides, rivers, etc. This tissue, when left alone "lives," i.e., has its D.C. potentials. But, when it is stimulated from without or from within, an astonishing change takes place. It moves actively, withdraws, strikes out. Associated with this defensive or aggressive movement there is an alternating current wave, a diphasic spike, which is lacking in the motionless tissues. An example of such tissue is a muscle fibre. When it is stimulated, it contracts, and a diphasic spike or group of such spikes occurs. This contractile tissue is primitive and found in all organisms that move, and is characterized by no electrical activity when quiet and by burst of such activity when stimulated to action (figure 1).

A similar structure, but more complicated, is nerve tissue. Primarily used to conduct stimuli to the contractile tissue, it acts like muscle in that it has no activity electrically when at rest, but when at work shows the same characteristic diphasic spike. Motion, as an inherent ability, however is not present in nerve tissue. (Figure 2.) In this tissue

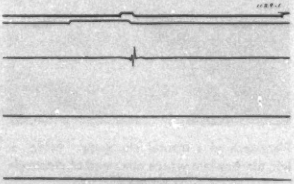

Figure 1. Electrical response of human biceps muscle to tap on tendon

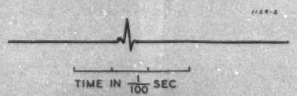

Figure 2. Action potential in a nerve fiber (from Gasser)

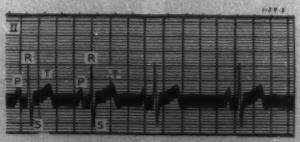

Figure 3. Action potentials of human heart (electrocardiogram—from P. D. White)

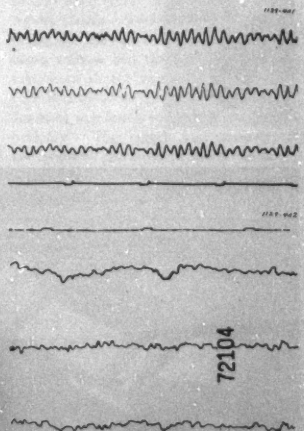

Figure 4A. Normal patterns of human brain potentials

Alpha rhythm above and beta rhythm below

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very rapid shifts of metabolic activity occur. For example, *A*, *B*, and *C* are points in line in such a piece of living matter. When at rest they are absorbing energy (being nourished, living) and are negative to their enveloping and supporting structures. Points *A*, *B*, and *C* are in, let us say, contractile tissue or nerve and have a much higher metabolic rate and complexity as far as molecular structure than the simple covering membrane. Hence they are all negative to it. If point *A* is stimulated its energy is released by a rapid chemical change and *A* loses its negative electrical charge. This in turn discharges or stimulates point *B* etc. These rapid changes produce the diphasic wave seen in muscle and nerve potentials. It is to be noted that in 3–4 thousandths of a second the whole process is completed. This nerve conduction proceeds not like electrons in a wire, but slowly as each adjacent point goes through a chemical breakdown and stimulates the next one. The rate of conduction of such an impulse is as far as 100 meters per second in man, but is much slower in lower animals (5 meters per second in reptiles).

A third type of electrical activity is associated with the more highly developed types of contractile tissue. Cilia, tubular digestive tracts, and heart muscle have a "beat" of their own and depend no longer on outside stimuli for their continuous, regular contractions and relaxations. Every "beat" has its accompanying bursts of diphasic waves. (Figure 3.) This shows a normal electrocardiogram. Metal (silver) discs covered with flannel soaked in salt are fastened with elastic bandage to the left wrist and left foot (lead II). Wires from the two discs lead to the poles of a sensitive string galvanometer. Bromide paper moved by clock works at 5 cm. per second receives the light beam from the mirror on the string. Thus electrical changes in the heart show up optically magnified on this recording paper when it is developed. Recording from each arm or right foot and left arm are some of the other leads (I and III). A vast and important field of clinical diagnosis has been developed in the interpretation of these EKG's as they are called. They indicate pathological changes in heart muscle, disturbances in rate, rhythm, and in circulation of blood in the heart muscle itself. No complete examination of the heart can be done without such a measurement. Every hospital now has one and many doctors have them at their disposal. In 1910 they were a curiosity in this continent.

The fourth type of body electrical currents is that associated with the complex tissue that makes up the central nervous system of animals. Here, as the function is continuous during life, the ganglia and brain cell tissues are ever-active electrically and show no periods of rest in the manner of muscle and nerve. (Figure 4.) Each brain cell does not actually beat alone, but by a system of interconnections keep each other stimulated to activity. These "chains" of neurones make up the bulk of the brain and spinal cord of man and animals. According to Herrick, in man, for example there are over $10^{2,783,000}$ possible neuronal combinations—a number far greater than the total sum of all atoms in the entire solar system 10^{76}.

It is this last form of living matter, the cells of the central nervous system that interests most physiologists today. In clinical medicine, the importance of the electrocardiogram in studying the function of the heart is completely established. The newer electroencephalogram or recording of the electrical activity of the

Figure 4B. Obtaining and recording human brain waves in the brain-wave laboratory of the Massachusetts General Hospital and the Harvard Medical School, Boston, Mass.

(Left). Electrodes used. Disc end fastened to scalp

Placement of a frontal electrode. Note, at left, the box into which other end of electrode is plugged

An ink-writing oscillograph recording a brain wave on moving paper

Apparatus room with two sets of amplifiers and two recorders

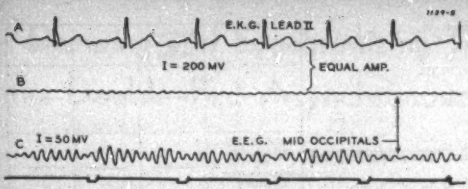

Figure 5. Comparison of human electrocardiogram and human electroencephalogram

In *B* the brain wave is at same amplification as the heart wave in *A*. In *C* the brain wave is at the standard amplification for recording

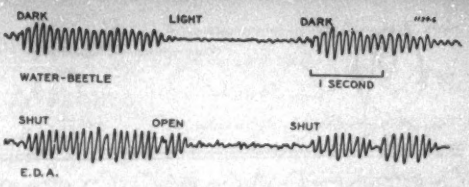

Figure 6. Comparison of the alpha rhythm in the beetle and human (from Adrian)

brain is rapidly becoming just as invaluable in the study of diseases and dysfunctions of the central nervous system. The recording of these brain waves, as the electroencephalograms are called, requires a much more sensitive type of apparatus. The heart currents obtained with surface electrodes on two of the extremities, as previously described, may reach nearly a millivolt and can be recorded directly by a string galvanometer. The brain currents picked up from small (5 mm.) lead discs attached to the scalp by electrode paste and collodion (needles or cutting the hair are not necessary) are only $^1/_{20,000}$ of the heart's and require vacuum tube amplification before recording (see figure 4 *A*, *B*). Albert Grass of Harvard and Dr. Alfred Loomis of Tuxedo Park both have developed rugged efficient battery and power-operated, push-pull amplifiers that operate ink-writing oscillographs. Offner of Chicago, Garceau of Holliston, Mass., and Rhem of New York, are other engineers who have apparatus in this field. By these brain wave machines the EEG, as the records are called, appear immediately as an ink line on the paper strip. The usual speed of the paper is 3 cm. per second and there are anywhere from 3 to 6 separate "channels" recording simultaneously. Normal human brain waves consist of two sorts. Alpha or 10 per second waves have voltages of 30 to 75 microvolts, are extremely regular, and when dominating the record are associated with easy-going stolid, reliable types (alpha type). The second type of normal activity is beta waves, 20–24 per second of voltages from 10 to 40 microvolts. They are often associated in general with tense, rather high strung people. There are so many exceptions and mixed types that the brain wave pattern is not a real index of personality, intelligence, or state of mind.

(Figure 5.) This shows a brain wave and a heart wave compared. Here is seen the regularity of the 10 per second alpha waves, their continual appearance and the smallness of the voltage as differing from the regularity, discreteness, and high voltage of the heart activity.

(Figure 6.) This shows the phenomenon of the disappearance of the alpha waves when light enters the eye. Professor Adrian of Cambridge University kindly lent me this slide. The lower tracing is from the brain of the famous Nobel Prize winner, the upper from his lowly compatriot, the English Water Beetle. Brain cells, wherever gathered together, act electrically much the same.

(Figure 7.) This shows what the human brain waves are like during sleep. Irregularity and increased voltage are characteristic. Response of the individual to outside stimulus is greatly prolonged. Here the reaction time was over five seconds. (Normal is $^1/_4$ of a second.) In very deep sleep, or when the individual is under anaesthesia, the rhythm becomes slower (3 per second) and the voltages increase. Such waves are called Delta waves. When the brain function is interfered with abnormal waves appear in the electroencephalogram. These seem to result from faster smaller waves being built up into some sort of synchrony. They appear as high-voltage spikes (100 to 200 microvolts) or high-voltage, slow waves (Delta waves). They are something like the sleep waves but usually of more voltage and slower. Periodic disturbances in the normal brain rhythm (cerebral dysrhythmia as it is called by Lennox) are found in patients who have epilepsy. The length and severity of the seizures (seconds to many minutes) are shown by the amount and voltage of these abnormal waves.

(Figure 8.) Record of brain waves of a person who has, clinically, a form of epilepsy. The seizures are short, lasting but a few seconds, and are often periods

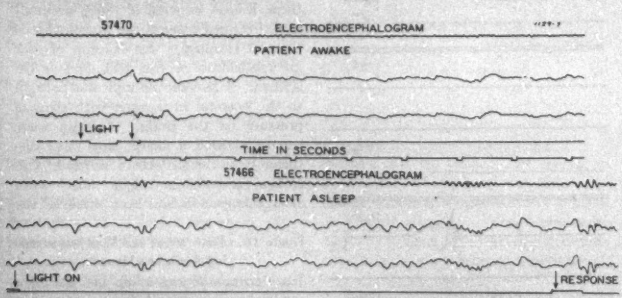

Figure 7 (above). Effect of sleep on brain waves and reaction

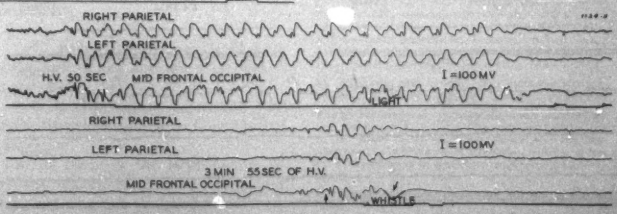

Figure 8 (right). Example of brain waves during a petit mal attack

Upper tracing shows long delay in responding to light. Lower tracing shows beginning of another attack probably stopped by whistle stimulus

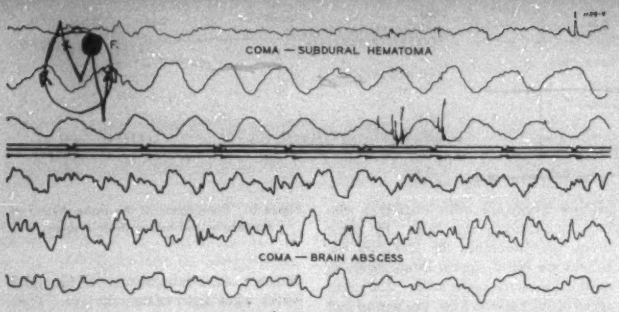

Figure 9. Brain waves from two patients in coma; upper waves from blood clot on brain and lower waves from brain abscess

	MUSCLE OR NERVE	HEART	BRAIN
IN DEATH I			
ABLE TO BE STIMULATED, NO SPONTANEOUS ACTIVITY II	*		
SPONTANEOUS SYNCHRONOUS ACTIVITY III		*	
ASYNCHRONOUS SPONTANEOUS ACTIVITY IV			*

Figure 11. In death I all tissues show no electrical activity; in II only muscle and nerve are normal; * in III heart is normal; * muscle and brain abnormal; in IV only brain is normal*

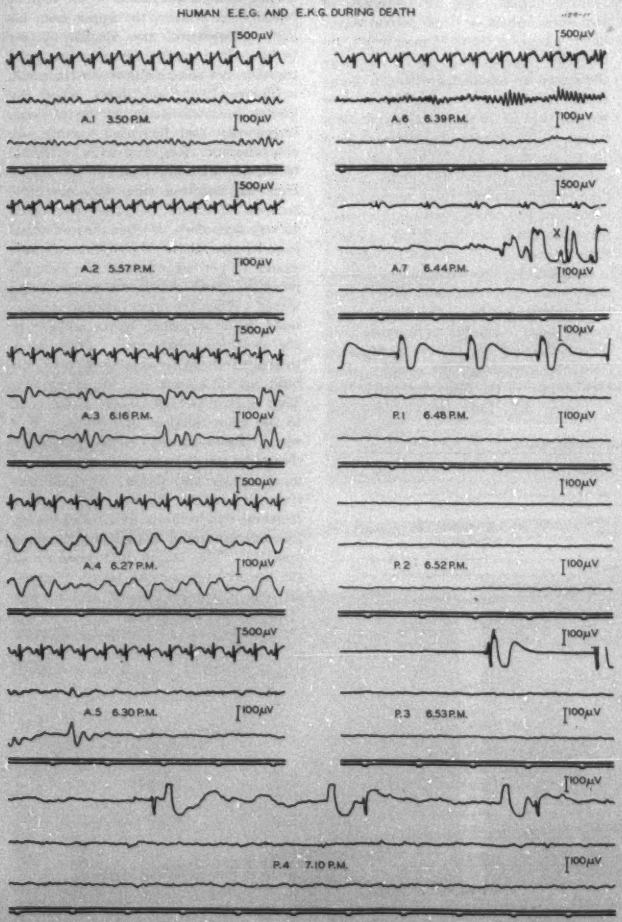

Figure 10. Brain waves and heart waves during death in a human

The electrocardiogram is top line and right and left brain waves are below. Brain waves disappear ten minutes before death. Legal death occurs at the spot marked (x) which indicates cessation of respiration and pulse. (x marks instant when intern placed stethoscope on chest to prove inaudible heart beat. The artifact produced by stethoscope touching electrode wire is shown in the tracing.) Electrocardiogram continues one minute after death, stops and then begins again. Thirty-two minutes after death heart still has three beats from pressure on chest

of unconsciousness. Sometimes they show up as slight twitchings of various face muscles, but do not develop into a real convulsion. These lapses are accompanied by a characteristic wave pattern called *the wave-spike formation*, which is a slow delta followed by a short spike. In this case, the person did not respond to the neon light signal, but did to the extremely unusual stimulus of the sound of a tug-boat whistle. During severe attacks of this kind, many fail to respond even to such a noisy stimulus.

Blood clots and tumors of the brain also cause these high-voltage, abnormal waves. By means of triangulation and phase shifts with the multiple channel sets of apparatus accurate localization of these lesions is possible (84% accuracy in 400 verified cases at the Massachusetts General Hospital). An example of such an application of this technique is described. A 38-year old man was brought to the hospital in a coma with signs of pressure on the brain. A brain wave tracing showed a sharp, slow-wave disturbance on the left side of his head. Operation revealed a tumor. Six weeks after this growth had been removed the

Damping and Synchronizing Torque of the Double-Fed Asynchronous Machine

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I. Introduction

THE double-fed asynchronous machine has become important in recent times as fan drive with wide speed range. The system consists of five main machines and the fan (see figure 1). It has many springs, masses, and dampings and therefore many natural frequencies. In order to determine these frequencies, i.e. the dynamic stability of the system, the damping and synchronizing torques of all parts of the system have to be known. Some papers have been published concerning the torques of the synchronous machine. It is easy to determine torques for the D.C. machines of the system. The object of this paper is to derive formulas for the damping and synchronizing torque of the double-fed asynchronous machine. As in the case of the synchronous machine, a complicated derivation and complicated results cannot be avoided.

II. The Differential Equations of the Double-Fed Machine

In order to simplify the mathematical work a two phase machine will be considered, and the usual assumptions, i.e. no saturation and small oscillations, are made. The results will be generalized for the m_1-phase machine. The voltage equations of the two phase machine are (for the symbols see List of Symbols)

$$E_{L1}\sin \omega t = AB_{I}' + L_1\dot{i}_{I}' + r_1 i_{I} \tag{1}$$

$$-E_{L1}\cos \omega t = AB_{II}' + L_1\dot{i}_{II}' + r_1 i_{II} \tag{2}$$

$$E_{L2}\sin(s\omega t+\delta) = AB_d' + L_2\dot{i}_d' + r_2 i_d \tag{3}$$

$$-E_{L2}\cos(s\omega t+\delta) = AB_q' + L_2\dot{i}_q' + r_2 i_q \tag{4}$$

where

$$A = \frac{2}{\pi} r_p l_\delta \omega \times 10^{-8} \tag{5}$$

i_{I}, i_{II}, i_d, and i_q are the currents in the four windings. B_{I}, B_{II}, B_d, and B_q are the resultant inductions in the axes of the winding produced by all currents. Between the inductions consists the relation[1]

$$B_{I} = B_d\cos\gamma - B_q\sin\gamma$$
$$B_{II} = B_d\sin\gamma + B_q\cos\gamma \tag{6}$$

where

$$\gamma = \frac{x}{\tau}\pi \tag{7}$$

is the angle between the axes of phase I of the stator and phase I of the rotor. For the inductions B_d and B_q the following equations hold

$$B_d = \frac{x_m}{A\omega}(i_d + i_{I}\cos\gamma + i_{II}\sin\gamma)$$

$$B_q = \frac{x_m}{A\omega}(i_q + i_{II}\cos\gamma - i_{I}\sin\gamma) \tag{8}$$

With two new variables

$$I_d = i_{I}\cos\gamma + i_{II}\sin\gamma$$
$$I_q = -i_{I}\sin\gamma + i_{II}\cos\gamma \tag{9}$$

the total torque of the machine will be[1,2]

$$T = A\omega(B_qI_d - B_dI_q) \tag{10}$$

With

$$\gamma = \frac{x}{\tau}\pi = \omega_{rav.}\,t + \epsilon = \omega_{rav.}\,t + \epsilon_0\sin st \tag{11}$$

and

$$\alpha = s\omega + s \qquad \beta = s\omega - s \tag{12}$$

the following four simultaneous differential equations will be found after some conversions.

$$E_{L1}\left(\cos s\omega t + \frac{\epsilon_0}{2}\cos\beta t - \frac{\epsilon_0}{2}\cos\alpha t\right) = -A(B_d\beta' + B_q') - L_1(I_d\beta' + I_q') - r_1I_q \tag{1a}$$

$$E_{L1}\left(\sin s\omega t + \frac{\epsilon_0}{2}\sin\beta t - \frac{\epsilon_0}{2}\sin\alpha t\right) = A(B_d' - B_q\beta') + L_1(I_d' - I_q\beta') + r_1I_d \tag{2a}$$

$$E_{L2}\sin(s\omega t+\delta) = (1+r_2)AB_d' + \frac{A\omega}{x_m}r_2B_d - L_2I_d' - r_2I_q \tag{3a}$$

$$E_{L2}\cos(s\omega t+\delta) = (1+r_2)AB_q' + \frac{A\omega}{x_m}r_2B_q - L_2I_q' - r_2I_q \tag{4a}$$

III. The Torques

A straightforward solution of the four equations is possible. For the four variables has been found

$$B_d = -E_{L1}\frac{x_m}{A\omega}\left[(a_s\cos s\omega t - b_s\sin s\omega t) - \frac{\epsilon_0}{2}(a_{11}\cos\beta t - b_{11}\sin\beta t) - \frac{\epsilon_0}{2}(a_s\cos\alpha t - b_s\sin\alpha t)\right] \tag{13}$$

$$B_q = -E_{L1}\frac{x_m}{A\omega}\left[(a_s\sin s\omega t + b_s\cos s\omega t) - \frac{\epsilon_0}{2}(a_{11}\sin\beta t + b_{11}\cos\beta t) - \frac{\epsilon_0}{2}(a_s\sin\alpha t + b_s\cos\alpha t)\right] \tag{14}$$

brain wave was normal again in this area.

(Figure 9.) Abnormal, slow-wave pattern obtained from a patient unconscious due to large blood clot on the brain. Abscesses and injuries to the brain can also be localized by this method.

(Figure 10.) Changes in the electrocardiogram and electroencephalogram occurring in a patient dying from cerebral hemorrhage. Electrical activity of the brain in this case ceased before that of the heart.

(Figure 11.) Table of comparison of normal electrical pattern of muscle, heart, and brain. A normal muscle lives at the second level of no electrical activity except on stimulus. When a muscle "beats" rhythmically and continuously, it is a diseased or dying tissue. The heart lives a normal life at this level of rhythmic discharge, and is abnormal when it depends on outside stimulus. The brain exists normally in the fourth level of continuous, arhythmic and asynchronous activity.

Summary

D.C. potentials are associated with static cellular life and are a product of metabolism.

A.C. potentials are associated with many tissues controlling or responding to movement.

Brain tissue is the most highly developed and exists normally in a state of constant, irregular electrical activity.

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1. For all numbered references, see list at end of paper.

$$I_d = -E_{L1}\left[(a_{14}\cos s\omega t - b_{14}\sin s\omega t) - \frac{e_2}{2}(a_{12}\cos\beta t - b_{12}\sin\beta t) - \frac{e_3}{2}(a_{13}\cos\alpha t - b_{13}\sin\alpha t)\right] \quad (15)$$

$$I_q = -E_{L1}\left[(a_{14}\sin s\omega t + b_{14}\cos s\omega t) - \frac{e_2}{2}(a_{12}\sin\beta t + b_{12}\cos\beta t) - \frac{e_3}{2}(a_{13}\sin\alpha t + b_{13}\cos\alpha t)\right] \quad (16)$$

where

$$\lambda_1 = \frac{r_2^2 + \left(\frac{\alpha}{\omega}\right)^2(1+\tau_2)x_2x_m}{r_2^2 + \left(\frac{\alpha}{\omega}\right)^2 x_2^2}$$

$$\lambda_2 = \frac{\frac{\alpha}{\omega}x_m r_2}{r_2^2 + \left(\frac{\alpha}{\omega}\right)^2 x_2^2}$$

$$\mu_1 = \frac{r_2^2 + \left(\frac{\beta}{\omega}\right)^2(1+\tau_2)x_2x_m}{r_2^2 + \left(\frac{\beta}{\omega}\right)^2 x_2^2}$$

$$\mu_2 = \frac{\frac{\beta}{\omega}x_m r_2}{r_2^2 + \left(\frac{\beta}{\omega}\right)^2 x_2^2}$$

$$\nu_1 = \frac{r_2^2 + s^2(1+\tau_2)x_2x_m}{r_2^2 + s^2x_2^2}$$

$$\nu_2 = \frac{sx_m r_2}{r_2^2 + s^2x_2^2}$$

$$a = r_2 + K(r_1\cos\delta - x_1\sin\delta)$$

$$a_1 = \frac{ar_2 + bsx_2}{r_2^2 + (sx_2)^2}$$

$$a_2 = x_m + (r_1\nu_2 + x_1\nu_1)$$

$$a_3 = \frac{a_1a_2 + b_1b_2}{a_2^2 + b_2^2}$$

$$a_4 = \frac{z}{\omega}(x_m + x_1\nu_1)$$

$$a_5 = a_2a_4 - b_2b_4$$

$$\alpha' \text{ for } \omega + z$$

$$a_6 = \frac{\alpha'}{\omega}x_m + \left(r_1\lambda_2 + x_1\frac{\alpha'}{\omega}\lambda_1\right)$$

$$a_7 = a_5 + 1 + K\frac{z}{\omega}x_1\frac{r_2\sin\delta - sx_2\cos\delta}{r_2^2 + (sx_2)^2}$$

$$a_8 = \frac{a_6a_7 + b_6b_7}{a_6^2 + b_6^2}$$

$$a_9 = \frac{\beta'}{\omega}x_m + \left(r_1\mu_2 + x_1\frac{\beta'}{\omega}\mu_1\right)$$

$$a_{10} = a_5 - 1 + K\frac{z}{\omega}x_1\frac{r_2\sin\delta - sx_2\cos\delta}{r_2^2 + (sx_2)^2}$$

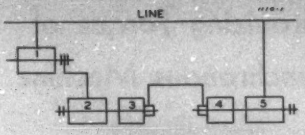

Figure 1. The double-fed asynchronous machine system

1. Double-fed asynchronous machine
2. Synchronous machine
3, 4. D-c machines
5. Synchronous machine

$$a_{11} = \frac{a_9a_{10} + b_9b_{10}}{a_9^2 + b_9^2}$$

$$a_{12} = a_{11}\mu_1 - b_{11}\mu_2$$

$$a_{13} = a_9\lambda_1 - b_9\lambda_2$$

$$a_{14} = (a_3\nu_1 - b_3\nu_2) + K\frac{r_2\sin\delta - sx_2\cos\delta}{r_2^2 + (sx_2)^2}$$

$$b = sx_2 + K(r_1\sin\delta + x_1\cos\delta)$$

$$b_1 = \frac{br_2 - asx_2}{r_2^2 + (sx_2)^2}$$

$$b_2 = -(r_1\nu_1 - x_1\nu_2)$$

$$b_3 = \frac{b_1a_2 - a_1b_2}{a_2^2 + b_2^2}$$

$$b_4 = \frac{z}{\omega}x_1\nu_2$$

$$b_5 = a_2b_4 + b_2a_4$$

$$\beta' = \omega - z$$

$$b_6 = -\left(r_1\lambda_1 - x_1\frac{\alpha'}{\omega}\lambda_2\right)$$

$$b_7 = b_4 - K\frac{z}{\omega}x_1\frac{r_2\cos\delta + sx_2\sin\delta}{r_2^2 + (sx_2)^2}$$

$$b_8 = \frac{a_6b_7 - b_6a_7}{a_6^2 + b_6^2}$$

$$b_9 = -\left(r_1\mu_1 - x_1\frac{\beta'}{\omega}\mu_2\right)$$

$$b_{10} = b_4 - K\frac{z}{\omega}x_1\frac{r_2\cos\delta + sx_2\sin\delta}{r_2^2 + (sx_2)^2}$$

$$b_{11} = \frac{a_9b_{10} - b_9a_{10}}{a_9^2 + b_9^2}$$

$$b_{12} = b_{11}\mu_1 + a_{11}\mu_2$$

$$b_{13} = a_9\lambda_2 + b_9\lambda_1$$

$$b_{14} = (a_3\nu_2 + b_3\nu_1) - K\frac{r_2\cos\delta + sx_2\sin\delta}{r_2^2 + (sx_2)^2}$$

From equations 10, and 13 to 16 the torques of a m_1-phase machine are

Constant torque

$$T_s = m_1E_{L1}^2x_m(a_9b_{14} - b_9a_{14}) \text{ watts} \quad (17)$$

Damping torque

$$T_d = m_1E_{L1}^2x_m\frac{1}{2s}[a_8(b_{13}+b_{12}) - b_8(a_{13}+a_{12}) + b_{14}(a_8+a_{11}) - a_{14}(b_8+b_{11})] \text{ watt-sec} \quad (18)$$

Synchronizing torque

$$T_s = m_1E_{L1}^2x_m\frac{1}{2}[a_3(a_{12}-a_{13}) + b_3(b_{12}-b_{13}) + a_{14}(a_8-a_{11}) + b_{14}(b_8-b_{11})] \text{ watts} \quad (19)$$

A simple expression for the constant torque has been given in a previous paper.[3]

While the torques of the synchronous machine depend on the angle δ and the excitation, the torques of the double-fed asynchronous machine depend on the angle δ, the secondary voltage, and the slip.

The derivations made above are valid when the synchronous machine (machine 2, figure 1) is larger than the asynchronous machine, for example, when two or more asynchronous machines are connected in parallel to a single synchronous machine and the oscillation of one of the asynchronous machines is considered. In this case the secondary voltage can be assumed independent of the oscillation and proportional to the average slip (equations 3*a* and 4*a*). When the synchronous machine is of the same size as the asynchronous machine the change of the slip has to be taken into acount in the equations 3*a* and 4*a*. The results in this case become much more complicated than in the case considered.

List of Symbols

INDEX 1—STATOR—INDEX 2—ROTOR

E_L terminal voltage

$K = \frac{E_{L2}}{E_{L1}}$

l_i ideal core width
L leakage coefficient
m_1 number of phases of the stator
N number of turns per phase
r resistance
s slip
x leakage reactance
x_m reactance due to the main flux
z angular velocity of the oscillation
δ angle between primary and secondary voltage

$\tau_1 = \frac{x_1}{x_m}$, $\tau_2 = \frac{x_2}{x_m}$ leakage coefficients

τ_p pole pitch

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Relative Accuracy of Three-Phase Metering Combinations

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Synopsis: This paper grades several three-phase combinations of instrument transformers and watthour meters under various conditions according to their approach to the best standard practice. The combinations are described and sources of uncertainty or of error are discussed. Diagrams are included to show the schematic connections of the component transformers and meters, both separately and in combination and of the power systems to be metered.

Introduction

FROM time to time questions arise in regard to the accuracy of three-phase metering combinations of instrument transformers and watthour meters. A definite estimate of the accuracy to be expected can usually be made for a given installation if sufficient details are available. However, in many cases all that is required is an idea of the relative accuracy obtainable. To meet such situations, relative accuracy under various conditions is here assigned to typical metering combinations now in use and to others sometimes proposed. These combinations are considered principally from the instrument-transformer standpoint. Operating and metering difficulties sometimes encountered with Y-connected potential transformers and the effects of various secondary interconnections on the metering accuracy are discussed. Much of this discussion applies to three-phase indicating wattmeters as well as to watthour meters.

A summary of the paper is given in table I, wherein the relative accuracy is graded from A to E. Grade A is assigned to cases where the metering combination and the conditions of application represent the best standard practice, which ordinarily embodies a close approach to the ideal. Three of the four power systems included are classified as three-phase, three-wire. There are five instrument transformer combinations and three types of watthour meters: 2-element, $2\frac{1}{2}$-element, and 3-element, respectively. In each case, sufficient comments are included to make table I reasonably self-explanatory. Table I is supplemented by figures 1 to 4, which show the schematic connections of the different parts and also of six complete metering applications.

It should be kept in mind that the ideal polyphase metering combination from the standpoint of accuracy is one that can be resolved into two or more component single-phase sections. Each section consists of one potential transformer, one current transformer, and one meter element. The instrument transformers can be checked for accuracy at any time and a portable single-phase indicating wattmeter or a watthour-meter standard can be added to the secondary meter circuits. Thus the accuracy of the polyphase combination can be verified to the satisfaction of any legal authority from the summation of two or more sets of single-phase results obtained simultaneously. For the highest accuracy, complete single-phase sections should be used as standards entirely separate from the polyphase combination. However, the accuracy obtainable with either method will not be uniform over wide ranges of power factor or load.

Power Systems

Three-Phase Three-Wire Systems

These systems may be classified according to the treatment of the system neutral. Systems with isolated neutral (figure 1*a*) or with a ground at one neutral point only (figure 1*b*) are common and require no special comments. Ordinarily it is immaterial from the metering standpoint whether the neutral is isolated or is grounded at one point either solidly or through low or high impedance; a ground-fault neutralizer (Petersen coil) constitutes an example of a high-impedance ground. Separate classifications for the two systems are justified, since single-phase loads could be connected between any line and ground with single-grounded neutral systems, particularly if the neutral is grounded through a low impedance, whereas such loading is not possible with isolated-neutral systems. For systems grounded at but one neutral point, it is assumed that there will be no line-to-ground loads.

Systems grounded at more than one neutral point (multiple grounds—figure 1*c*) in the manner shown probably should be considered as three-phase, four-wire systems, even if not so classified, not only because single-phase loads could be connected between any line and ground as just pointed out, but particularly because such loads can now be applied through the Y-Y-connected power transformers. These transformers often are provided with tertiary windings for closed-delta connection to take care of the triple harmonics in the exciting currents.

Three-Phase, Four-Wire Systems

This classification applies to systems having four metallic conductors (figure 1*d*). Such systems also are common and usually supply single-phase loads connected between any line and the neutral in addition to three-phase, three- or four-wire loads. The system neutral may or may not be grounded at one or more points.

Instrument Transformers

The principal functions of instrument transformers are to insulate low-voltage

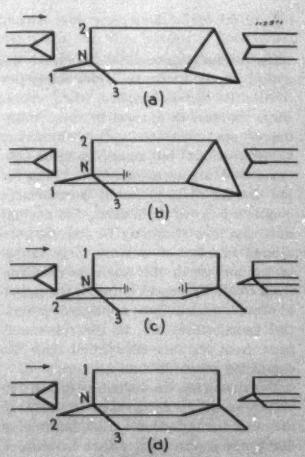

Figure 1. Three-phase power systems

Three-phase three-wire with
(*a*) Isolated neutral
(*b*) One neutral ground
(*c*) Multiple neutral grounds
Three-phase four-wire
(*d*) With or without neutral ground

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1. For all numbered references, see list at end of paper.

measurement devices from dangerous-to-life line voltages and to act as multipliers for them. In the instrument transformer combinations under consideration (figure 2), the current-transformer primaries are connected in the proper lines and their individual secondaries supply individual meter-current circuits. On the other hand, the potential-transformer primaries are connected either line-to-line or line-to-neutral, so their individual secondaries either supply individual meter potential circuits or constitute part of a network.

The currents and voltages obtained from the secondaries of instrument transformers usually represent the corresponding primary quantities with acceptable accuracy without making corrections for the respective ratio and phase angle errors, but such corrections for either the actual or the "average" characteristics frequently can be applied when necessary. Several exceptions to these statements are discussed under "Metering Considerations" but some of a more general nature are mentioned here. Thus for the case of three potential transformers connected closed-delta-delta, the normal unit characteristics may be considerably altered because of a fairly large circulating current in the windings resulting from small differences between the units. However, line-to-line connected potential transformers are, in general, much freer from various disabilities than Y-connected potential transformers.

For the latter, the three line-to-neutral voltages with isolated primary neutral may contain appreciable triple harmonics due to the suppression of such harmonics in the respective exciting currents; this distortion actually may cause an erroneous voltage indication, to say nothing about rendering normal transformer corrections of doubtful value. If the primary neutral is grounded, but if the system neutral is ungrounded either permanently or temporarily, the potential transformer line-to-neutral voltages may become very badly distorted and the neutral point, in effect, may even get outside of the supply-voltage triangle due to switching surges.[1,2,3]

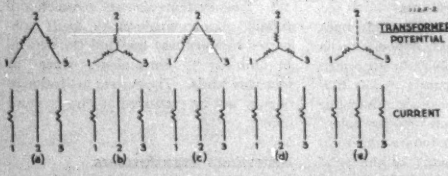

Figure 2. Instrument - transformer combinations for three-phase systems

Primaries of two current transformers and, *(a)* two potential transformers in open delta; *(b)* three potential transformers in wye. Primaries of three current transformers and, *(c)* two potential transformers in open delta; *(d)* three potential transformers in wye; *(e)* two potential transformers in part wye.

(a), (b), (c), (d) For three-phase, three-wire systems; *(d), (e)* for three-phase, four-wire systems

Watt-Hour Meters

Two-Element Meters (Figure 3*a*)

These meters have two separate driving elements, which may act either on separate disks mounted on a common shaft or on different segments of the same disk. Such meters are standard for three-phase, three-wire systems.

Two-and-One-Half-Element Meters (Figure 3*b*)

These meters also have two separate elements but each set of current coils is divided into two equal, separate sections. One section and the corresponding potential coil of one element are supplied from one system phase and the other similarly arranged element is supplied from a second system phase somewhat like a straight 2-element meter. Current from the third system phase flows in a reversed direction through the two extra meter current-coil sections in series and thus reacts with the voltages of the other two system phases applied to the two meter potential coils. The vector sum of these two phase voltages usually equals the voltage of the third phase, so it is evident that the "$1/2$-element" then operates correctly but with a synthetic instead of an actual third-phase voltage. However, this vector sum does not always correctly represent the third-phase voltage and under such conditions the "$1/2$-element" registration will be in error; of course, it contributes but one-third the torque and its error but one-third the effect in a balanced system.

These meters also are known as 2-element meters with split current coils. They are standard for three-phase, four-wire systems when the three voltages are approximately balanced and are used to avoid the extra potential transformer, wiring, and expense required for a 3-element meter.

Three-Element Meters (Figure 3*c*)

These meters have three separate elements which are supplied from the three phases of a three-phase, four-wire system for which they are standard under all conditions of load and of voltage balance. The meters are entirely satisfactory for three-phase, three-wire systems having one or more neutral grounds.

Metering Considerations

Single-Phase Metering

The metering of a single-phase system will serve as an introduction to the metering of polyphase systems. A single-phase system requires one potential transformer, one current transformer, and one watthour meter. Certificates for the two instrument transformers will give the respective ratio correction factors to within 0.1 per cent and the phase angles to within three minutes. The watthour meter can be adjusted to be correct within say 0.3 per cent over a medium load range. Thus an overall accuracy within 0.5 per cent over such a load range near unity power-factor could be expected, even if the errors were all in the same direction, which would be most unusual. Better accuracy can be obtained at a definite and fairly steady load point by taking the average of a large number of observations on a high-grade portable indicating wattmeter, which can be checked to within 0.15 per cent over the upper part of its scale. On a similar basis, an overall accuracy within 0.35 per cent could be expected under this condition.

The single-phase metering combination just described represents the simplest case, where the corrections determined for the individual parts can readily be combined algebraically and an estimate made of the best accuracy obtainable. Since a polyphase power system consists in effect, of two or more out-of-phase single-phase systems, it should be obvious that the highest accuracy can be obtained only if single-phase metering conditions are maintained. This accounts for long-standing cautions against some "secondary interconnections" in polyphase metering circuits.

Three-Phase Three-Wire Metering

Applying this idea to a three-phase, three-wire, ungrounded system, two current and two potential transformers and two single-phase watthour meters would

Table I. Relative Accuracy

Case	System	Neutral	Pot. Trans. Pri.	Pot. Trans. Sec.	Pot. Trans. Meter	Connections	Meter	Comments	Figure	Accuracy Grade
3-Phase 3-Wire Systems										
2-element meter—2 current transformers—2 potential transformers										
1	*Isolated				Open	Δ	Open	Δ	Best standard practice	4a	A
2	**1 ground				Open	Δ	Open	Δ	Best standard practice	—	A
3	***Mult. gr.				Open	Δ	Open	Δ	L/N loads not metered correctly	—	D
2-element meter—2 current transformers—3 potential transformers										
4	Isolated	Iso./gr.	Gr.		Y-Y		Open	Δ	Indeterminate	—	C
5	1 ground	Iso./gr.	Gr.		Y-Y		Open	Δ	Indeterminate	4b	C
6	Mult. gr.	Iso./gr.	Gr.		Y-Y		Open	Δ	Indeterminate; related to *case 3*	—	B
3-element meter—3 current transformers—2 potential transformers										
7	Isolated		Iso.		Open	Δ	Y		Indeterminate	—	C
8	1 ground		Iso.		Open	Δ	Y		Indeterminate	4c	C
9	Mult. gr.		Iso.		Open	Δ	Y		Indeterminate	—	C
3-element meter—3 current transformers—3 potential transformers										
10	Isolated	Iso./gr.	Gr.	Iso.	Y-Y		Y		Indeterminate	—	C
11	1 ground	Iso./gr.	Gr.	Iso.	Y-Y		Y		Indeterminate	4d	C
12	Mult. gr.	Iso./gr.	Gr.	Iso.	Y-Y		Y		Indeterminate	—	C
13	Isolated	Gr.		Gr.	Y-Y		Y		Neutral instability possible	—	C
14	1 ground	Gr.		Gr.	Y-Y		Y		Best standard practice	—	A
15	Mult. gr.	Gr.		Gr.	Y-Y		Y		Best standard practice	4e	A
3-Phase 4-Wire Systems										
3-element meter—3 current transformers—3 potential transformers										
16	Iso./gr.	† Iso./gr.	Gr.		Gr.	Y-Y		Y	Best standard practice	—	A
2½-element meter—3 current transformers—2 potential transformers										
17	Iso./gr.	† Iso./gr.	Gr.		Gr.	L/N		L/N	Standard practice	4f	B

NOTES: L/N = line-to-neutral; Iso./gr. = isolated or grounded.
*Figure 1a.
**Figure 1b—it is assumed that there will be no line-to-ground loads.
***Multiple grounds—figure 1c—these 3-phase, 3-wire systems probably should be considered as 3-phase, 4-wire systems and provision made for metering correctly single-phase loads connected between any line and neutral or ground.

†In *cases 16* and *17*, the potential-transformer and system neutrals are tied together; the system neutral may either be isolated from ground (figure 1d) or grounded at one or more points. See text for further comments on the 2½-element metering combination.

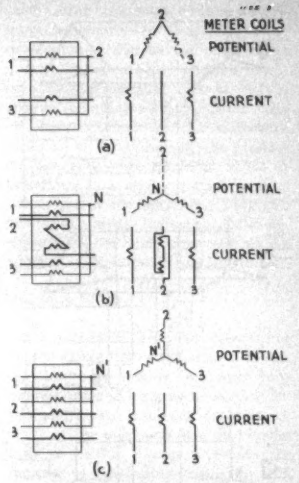

Figure 3. Polyphase watt-hour meters

(a) Two-element for three-phase three-wire systems

(b) Two-and-one-half-element for three-phase four-wire systems

(c) Three-element for three-phase three- or four-wire systems

be required and these would constitute two separate, single-phase metering circuits. Of course, such separate metering circuits are quite unusual, except for special tests. The meters are slightly handicapped by the fact that a phase displacement of 30 degrees exists between the line-to-line voltages and the line currents (at unity power factor).

Thus for *case 1* in table I (figure 4*a*), the first "secondary interconnection" occurs in the substitution of a 2-element polyphase watthour meter for the two single-phase meters, which necessitates an average correction for the instrument-transformer and meter-element errors. Other interconnections occur in the substitution of three secondary leads for four both for the current transformers and for the potential transformers. This tends to complicate the ratio and phase-angle tests, particularly if the secondary leads are long.

For balanced systems, the secondary current in the common lead will equal those in the other two leads, but will be 120 degrees out of phase with them and the resulting additional common burden for the two current transformers must be allowed for in making up the respective test burdens. If this common burden is large due to a long lead or to measurement or protective devices connected in series therewith, it will be necessary to know the phase sequence of the power system, as well as the actual phases in which the current transformers are connected in order to test them properly.

For two equal potential-transformer burdens, the current in the common potential lead will be $\sqrt{3}$ times those in the other two leads and 30 degrees out of phase with them; neglecting the voltage drop in the leads may cause appreciable errors in the ratio and phase-angle results. Further complications occur if a burden is connected across the open delta (third phase without potential transformer); even if its power factor is unity, it imposes its full voltamperes at 0.5 power factor on both potential transformers, leading in one case and lagging in the other, thus again making it necessary to know the phase-sequence of the power system and the connections of the individual transformers thereto: the importance of this proceeding increases with the magnitude of the burden. Somewhat similar considerations apply when double autotransformers are used to shift the phase of the potential transformer voltages to supply var- or voltampere-hour meters, since the net effect is to change the burden distribution. Interconnected, low-power-factor burdens sometimes have surprising effects: when two potential transformers supply such Y-connected burdens, not only does one transformer supply all the energy necessary, but it also tends to excite the other transformer secondary winding! This undesirable effect increases with the magnitude of the burdens and may be overcome by adding suitable non-inductive burdens.

In spite of the various uncertainties just outlined, some of which are inherent in the *case 1* metering combination, satisfactory accuracy is usually obtained. A similar statement applies when the power-system neutral is grounded at one point only as in *case 2*.* Thus the highest relative accuracy—grade A—is assigned to *cases 1* and 2.

A much greater degree of uncertainty exists when three Y-connected potential

Case 3 and others involving grounds at more than one power-system neutral point are discussed under "Three-Phase, Four-Wire Metering."

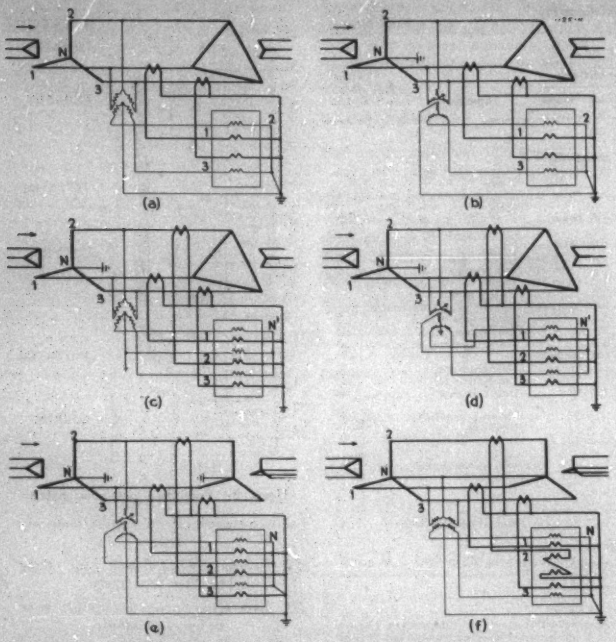

Figure 4. Schematic connections of three-phase metering combinations (cases outlined in table I)

(*a*) *Case 1* (figures 1*a*, 2*a*, 3*a*)
(*b*) *Case 5* (figures 1*b*, 2*b*, 3*a*)
(*c*) *Case 8* (figures 1*b*, 2*c*, 3*c*)
(*d*) *Case 11* (figures 1*b*, 2*d*, 3*c*)
(*e*) *Case 15* (figures 1*c*, 2*d*, 3*c*)
(*f*) *Case 17* (figures 1*d*, 2*e*, 3*b*)

transformers are substituted for two connected open delta to supply the two potential circuits of a 2-element meter as in *cases 4* and *5* (figure 4*b*). Here it is impossible not only to allocate properly the three individual potential transformer corrections, which may differ slightly, but also to resolve the combination into component single-phase metering circuits, which is much more important. The three line-to-neutral transformer voltages will be distorted (peaked) if the primary neutral is isolated and may be distorted if it is grounded with system neutral isolated, as was pointed out under "Instrument Transformers." However, the secondary line-to-line voltages applied to the two meter circuits will not be distorted, assuming sine-wave supply voltages. The uncertainty necessitates assigning a considerably lower relative accuracy—grade C—to *cases 4* and *5*.

A similar indeterminate situation exists when two open-delta connected potential transformers are used to supply the three Y-connected potential circuits of a 3-element meter as in *cases 7* and *8* (figure 4*c*), which is sometimes recommended for low-power-factor loads on three-phase, three-wire systems. Here the three line-to-neutral meter voltages are somewhat distorted due to the suppression of the triple harmonics in the exciting currents. Such distortion will not occur if the inductive meter circuits are replaced by noninductive wattmeters.

The foregoing situation is not improved by the substitution of three Y-connected potential transformers for the two in open delta, if the two secondary neutral points are not connected as in *cases 10* and *11* (figure 4*d*). Here again as in *cases 4* and *5*, the three line-to-neutral transformer voltages will be distorted if the primary neutral is isolated and may be distorted if it is grounded with system neutral isolated, but the secondary line-to-line voltages applied to the Y-connected meter circuits will not be distorted with a sine-wave supply.

The indeterminate features of *cases 10 and 11* are partly overcome by connecting the potential-transformer-secondary and meter-potential-circuit neutral points as in *case 13*. However, the three line-to-neutral voltages may be distorted and potential-transformer-neutral instability may result as with similar neutral conditions in *cases 4* and *10*, due to the attempt to ground the power system through the potential transformers. Because of this, *case 13* is assigned relative-accuracy grade C also.

Grounding the power-system neutral at one point as in *case 14* translates *case 13* into standard practice. *Case 14* closely approaches the ideal of component single-phase metering sections mentioned in the "Introduction." The eight secondary leads (as in figure 4*e*) are practically equivalent to twelve, since the currents in the two common leads normally are negligible. Three single-phase watt-hour meters may readily be added for verification purposes and each meter or meter element operates at the same power factor as that of the load in its respective phase, which is particularly advantageous at low power factors. This favorable condition does not exist with balanced three-phase loads in *cases 1* and *2*; however, these are entitled to share relative-accuracy grade A with *case 14* for most applications.

Three-Phase Four-Wire Metering

A 3-element meter with three current and three potential transformers as in *cases 14*, *15* (figure 4*e*) and *16* is standard both for three-phase, three-wire systems with at least one neutral point grounded and for three-phase, four-wire systems. Relative-accuracy grade A is assigned to this metering combination. Three-phase, three-wire systems with multiple neutral grounds are equivalent in many respects to three-phase, four-wire systems, even if not so operated with single-phase loads connected between any line and the neutral ground.

A $2^1/_2$-element meter with three current and two potential transformers as in *case 17* (figure 4*f*) is standard for the usual condition where the three line-to-neutral voltages of the three-phase, four-wire system are fairly well balanced; relative-accuracy grade B is assigned to this metering combination.

Although designed primarily for three-phase, four-wire systems, it should be evident from a consideration of *cases 16* and *17* that the $2^1/_2$-element metering combination can be substituted for the 3-element metering combination in *cases 14* and *15*. Relative-accuracy grade B would then be assigned unless the system-neutral grounds are effected by means of ground-fault neutralizers; the line-to-neutral voltages may then be consider-

Impulse Strength as a Measure of Cable Quality

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Synopsis: Testing cables by means of the impulse generator, originally developed for use in studying the effect of lightning on cables, is becoming recognized more and more as a useful method for determining cable quality. It is felt that the amount of data accumulated during the past ten years is sufficiently large to be used in formulating a theory concerning the factors governing the impulse strength of cables. It is indicated in this paper that maximum rather than average stress should be taken into account when impulse test results are evaluated, since the maximum stress at breakdown is a measure of the quality of the insulation alone. This view is contrary to that generally accepted in this country although some workers in this field abroad have accepted this theory for some time.

Introduction

THE Detroit Edison Company has in the past sponsored a number of tests to determine the impulse strength of various types of cable in relation to other electrical equipment. Results of some of these tests on "solid-type" impregnated paper (24 and 4.8 kv) and varnished cambric (4.8 kv) cables were published by McCabe[1,2] from time to time. About two years ago the scope of these tests was enlarged to include various types of impregnated paper insulated cables proposed for extra-high voltage service as no impulse test data were then available on such cables. Held and Leichsenring[3] and Foust and Scott[4] have since published results of impulse tests on oilfilled cables.

Oilfilled, oilostatic, compression, and gas-filled (Beaver) cables were in commercial use two years ago at voltages above those recommended for solid type cables. As gas-filled cable was not on hand, oilfilled, oilostatic, and compression cables having equal insulation thicknesses, were tested. The results of these tests indicated that maximum rather than average stress determines the impulse strength of the cable. In order to verify this statement, tests were made on solid type cables of various conductor diameters, conductor surfaces and insulation thicknesses, and on low gas pressure cables. In computing average stresses at breakdown on the solid type cables, no definite correlation could be established between these data and the quality of the insulation as observed by examination of the samples. On the other hand, when maximum stresses at breakdown were computed, values were obtained that showed pronounced increase with improving insulation, reaching a constant maximum value at the best obtainable impregnation. Further tests on oilfilled cables showed that uniformity of taping as determined by the Mildner diagram affects the maximum stress at breakdown in a similar manner as does the degree of impregnation. This correlation is a strong indication of the significance of the maximum stress as the criterion of quantitative breakdown.

Previous Work

No universally accepted theory has been proposed that would allow the computation of the impulse breakdown voltage of a cable of known construction details and known insulation qualities. A study of the published data on impulse tests of cables, however, permits the drawing of conclusions concerning certain factors that influence the impulse strength.

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1. For all numbered references, see list at end of paper.

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ably unbalanced due to unequal capacitances to ground of the three line conductors. Under this condition, the 3-element metering combination should be used. Of course, the straight 2-element metering combination (*case 2*) may be used for all such three-phase, three-wire systems if the single-phase loads to neutral are negligible or if these loads are balanced.

The limitations just placed on the application of 2-element metering combinations are important. In *cases 3* and *6*, for example, a load connected between the line without current transformer and ground would not be metered at all and the meter voltages would not have the proper magnitude or phase for loads connected between the other two lines and ground; this accounts for the low relative-accuracy grades D and E, respectively. The grade C accuracy assigned to the 3-element metering combination in *cases 9* and *12* is due to its being indeterminate and not to the possibility of incorrectly metering single-phase loads to ground.

In the foregoing discussion, the term "indeterminate" has been used to describe conditions where it is impossible to resolve the metering combination into component single-phase sections and thus to allocate instrument-transformer and meter corrections definitely. Although it need not be assumed that "indeterminate" is synonymous with "inaccurate," arguments advanced as to the correctness of such a metering combination may sound unconvincing. It should be emphasized that all important metering installations are at all times subject to verification or checking when questions arise in regard to their correctness.

Conclusions

A general idea of the performance to be expected from several three-phase metering combinations under various conditions is conveyed by the relative accuracy assigned thereto in table I. Among the many cases included, it should be possible to find examples approximating other cases sometimes used or proposed and thus permit grading them also. From the accompanying discussion, it should be evident that in cases where grade A is assigned to the metering combination, very satisfactory accuracy can be obtained if appropriate secondary connections are used and if the instrument-transformer corrections are properly applied.

References

1. Experiences With Grounded-Neutral, Wye-Connected Potential Transformers on Ungrounded Systems, C. T. Weller. AIEE Transactions, volume 50, 1931, pages 299–316.

2. Physical Nature of Neutral Instability, A. Boyajian and O. P. McCarty. AIEE Transactions, volume 50, 1931, pages 317–27.

3. Theory of Abnormal Line-to-Neutral Transformer Voltages, C. W. LaPierre. AIEE Transactions, volume 50, 1931, pages 328–42.

(a). Quality of Insulation

Held and Leichsenring[3] and Busse and Vogel[5] established that the use of denser papers results in higher impulse strength; and that temperature of the cable during the tests, provided the limits do not exceed those of commercial operation, does not measurably influence the impulse strength.[3] By inference, the latter signifies that the viscosity of the impregnating compound (which decreases as the temperature increases) has also a very limited effect on the impulse strength. Whether "straight" mineral oil is used to impregnate the cable or a mixture of mineral oil and rosin, appears to have no effect on the impulse strength of the cable. The degree of impregnation at a given temperature, however, seems to have a very decided effect.[1] That service aging of solid-type cables, which generally results in a decrease of the degree of impregnation, will also result in a proportional decrease of impulse strength is indicated[3] but this requires further study.

(b). Geometry of Cable and Surface of Conductor

The effect of conductor diameter (minimum radius) and conductor surface appears to have influenced the results of several workers. For instance when specially constructed copper conductors having the same diameter and smooth outer surface were used, the number of variables was reduced to such an extent that from the results obtained it was possible to disprove the theory still generally accepted in this country, that thinner insulation possesses a comparatively higher impulse strength.[3] Tests on cables with sector shaped conductors disclosed the fact that 80 per cent of the failures were on the "shoulder" (minimum radius of the conductor) of the sector.[1] The same author reports that strand-shielding improves the impulse strength considerably.[3] Davis and Eddy found that the impulse strength of rubber in sheet form is approximately 50 percent higher than that of rubber cable insulation of the same wall thickness.[6]

(c). Polarity of the Impulse Wave

Schneeberger,[7] in discussing the effect of polarity of the impulse wave on the impulse strength of a cable, indicated that when a positive wave was used, the breakdown value was 20 percent lower than with a negative wave. Later reports contradict this finding. One author has found no difference in oilfilled cables but in solid cables the impulse strength, using a negative wave, was from 5 to 13 percent lower than when a positive wave was used.[2] Another paper states that the authors found no difference in impulse strength due to variations in the shape and polarity of the impulse wave.[6]

In view of the above data, no definite conclusion can be drawn in regard to the effect of the polarity of the impulse wave on the impulse strength of the cable. For this reason, small variations in absolute values reported by various authors may exist, but the relative rating of the individual samples will probably still remain the same.

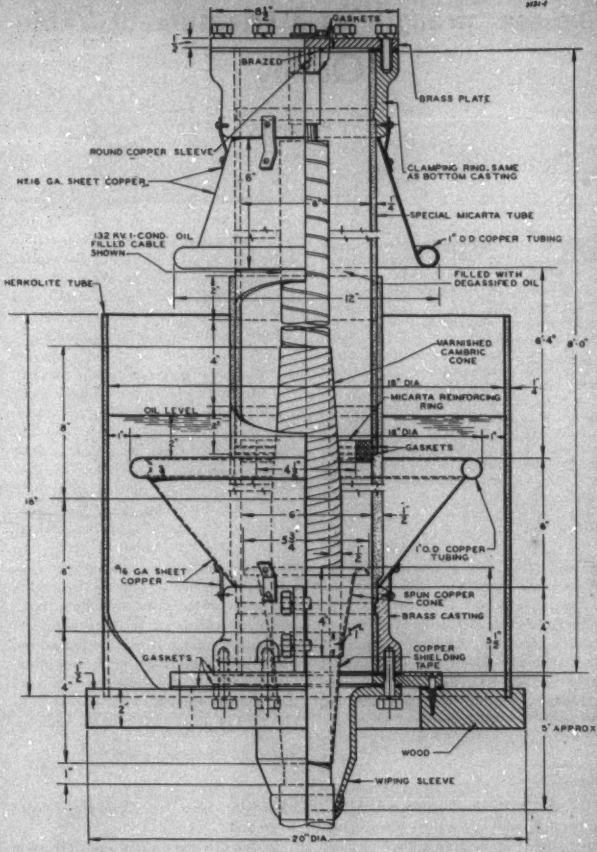

Figure 1. Impulse terminal assembly for high-voltage surge test

Method of Test and Testing Equipment

Engineers of The Detroit Edison Company favor the impulse testing of electrical apparatus with a negative wave because field testing has shown the prevalence and greater importance of negative lightning strokes in connection with transmission line outages. A method of testing with sufficiently high potential surge to obtain breakdown with one surge is also favored for reasons of simulating conditions in the field. All tests described in this paper, therefore, were made with negative wave and attempts were made to obtain breakdown with one surge.

The impulse generator used has been previously described.[1] For these tests additional condensers were used in series and both ends of the cable were encased in terminals built to withstand 1,000 kv and

200 psi pressure. Figure 1 shows the terminal assembly. Figure 2 shows the method used in connecting the cable to the impulse generator. Figure 3 is an oscillogram of the incident wave (approximately 0.05×24 microsecond) with the cable disconnected, and figure 4 is a typical wave recorded during breakdown of sample *J*1. It should be noted that the steepness of the wave front is somewhat lessened when the cable is connected to the generator.

Presentation of Results and Description of Samples

The results of the impulse tests which form the basis of this paper, are graphically illustrated in figure 5, and complete data are supplied in tables I and II.

represents minimum values of groups of measurements.

Pertinent information regarding the Detroit samples is given in the following:

Samples *A*1, *A*2, *I*1, and *J*1 were solid type, single-conductor cables. The *A* samples had a small conductor and thin insulation. Sample *I*1 had a conductor diameter similar to that of samples *E*1 to *E*4 (compression and oilostatic) but an insulation thickness almost twice as great (170%). Sample *J*1 had a large conductor diameter similar to that of samples *F*1, *F*2, *G*1, *G*2, *H*1, and *H*2 (oilfilled) but greater insulation thickness (130 and 111% respectively).

Samples *B*1, *B*2, *B*3, *B*4, *B*5, and *B*6 were low gas pressure, three-conductor, sector, shielded, 27.6-kv cables. Samples *B*1, *B*2, and *B*3 represent three conductors of one section and samples *B*4, *B*5, and *B*6 the three conductors of another section of the same cable. Ten complete failures were observed in the six samples, seven of which were at the "shoulders" of the sector.

Samples *C*1, *C*2, *C*3, *D*1, *D*2, and *D*3 were solid type, three-conductor, sector, shielded, 24-kv cables. The *C* samples represent the three conductors of one cable, while the *D* samples are the three conductors of another cable. The two cables were identical except for the strand-shielding with semi-conducting tapes employed in the latter group. The manufacturer who made these cables used the same type of paper, same taping machine, impregnated the two cables in the same tank, and lead covered both on the same day. Therefore, except for the strand-shielding, there should be no other variables. Failures in all six samples occurred at or near the "shoulder" of the sector.

Samples *E*1, *E*2, *E*3, and *E*4 were taken from the same oval-shaped, single-conductor cable. Samples *E*1 and *E*3 were tested in a steel pipe containing nitrogen under 200 psi (compression cable). *E*2 was tested as an oilostatic cable, that is, the armoring and lead sheath were removed, and the pipe that contained the cable was filled with oil under 200 psi. *E*4 was tested without the application of pressure; in other words, as a solid type cable. All four samples failed near the major axis of the oval conductor. Figure 6 shows the Mildner-diagram of cable *E*.

Samples *F*1, *F*2, *G*1, *G*2, *H*1, and *H*2 were taken from three single-conductor oilfilled cables made by three manufactur-

Table I

Tested in Detroit

No.	Type of Cable	r.	w.	R.	n.	Breakdown Volt. Kv	G. Avg. V/Mil	G. Max. V/Mil	Qual. of Taping	Degree of Impr.
*A*1	Solid	145	156	301	7	230	1,475	2,715	Fair	Fair
*A*2						225	1,440	2,060	Fair	Fair
*B*1	Solid	167	240	407	"Compact" strand	280	1,170	1,880	Very good	Very ltd.
*B*2	Low gas press.	167	240	407	"Compack" strand	300	1,250	2,010	Very good	Very ltd.
*B*3						300	1,250	2,010		
*B*4						315	1,310	2,110		
*B*5						320	1,330	2,150		
*B*6						335	1,400	2,250		
*C*1	Solid	151	281	432	Compack strand	380	1,350	2,390	Very good	Very good
*C*2						390	1,390	2,450		
*C*3						400	1,425	2,520		
*D*1	Solid	166	261	427	Strand shield	480	1,840	3,060	Very good	Very good
*D*2						485	1,860	3,090		
*D*3						500	1,915	3,180		
*E*1	Compr. Oilost. Compr.*	290	386	676	18	570	1,475	3,010	Very good	Very good
*E*2						580	1,500	3,060		
*E*3						585	1,515	3,080		
*E*4						630	1,630	3,320		
*F*1	Oil-filled	542	386	928	37	730	1,890	3,250	Very good	Very good
*F*2						775	2,010	3,450		
*G*1	Oil-filled	514	450	964	25	590	1,310	2,360	Very irr.	Very good
*G*2						680	1,510	2,720		
*H*1						820	1,820	3,280	Very good	Very good
*H*2						825**	1,835	3,300		
*I*1	Solid	340	656	996	18	760	1,160	2,700	Fair	Fair
*J*1	Solid	576	500	1,076	24	830	1,660	2,980	Fair	Fair

*Without pressure.
**No failure.
r. Minimum radius of conductor, mils.
w. Thickness of insulation.
R. Minimum radius over insulation.
n. Number of strands in outer layer.

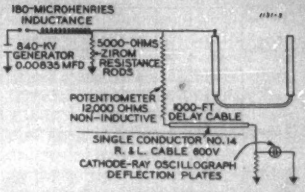

Figure 2. Impulse-generator wiring diagram

84 0.7-microfarad capacitors, 2 capacitors in series per bank. Capacitors charged to 20 kv per bank

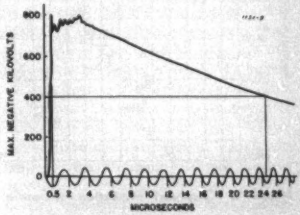

Figure 3. Oscillogram of incident wave

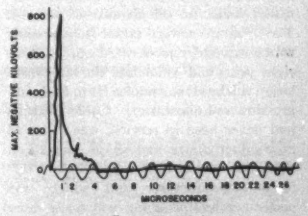

Figure 4. Typical breakdown wave

This chart was compiled to show breakdown voltage and maximum stress at breakdown, for all the samples tested in Detroit as well as those tested elsewhere, when sufficient data were available. It should be noted that the Detroit samples are designated by a letter and a number, each letter representing a cable and each number an individual measurement on a sample of the cable. The data published by Foust and Scott,[4] is represented by the same numbers the authors used in their paper. Number 34 refers to the paper cable sample used by Davis and Eddy[6] and numbers 35 to 40 represent the Held and Leichsenring samples.[5] It should be noted that this latter group

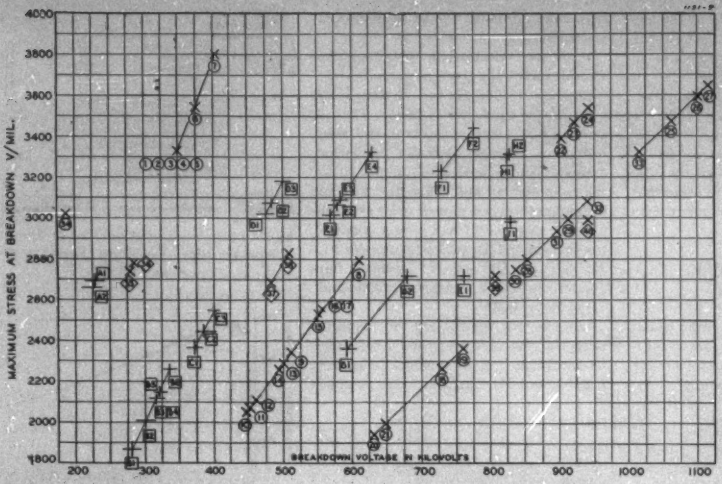

Figure 5. Graphical illustration of results

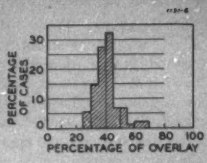

Figure 6. Mildner diagram of cable E

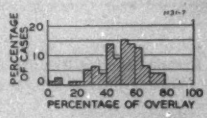

Figure 7. Mildner diagram of cable H

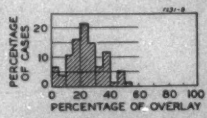

Figure 8. Mildner diagram of cable G

ers, respectively. All six samples were tested under an oil pressure of ten psi. The *F* samples were taken from a cable which was under accelerated aging test for eight years and which had the same insulation thickness as samples *E*1 to *E*4 (compression and oilostatic). Cable *G* which had never been in service, was identical in conductor size and shape, insulation thickness, etc. to cable *H*, made by a different manufacturer and which was under accelerated aging test for a short time. Figure 8 shows the Mildner-diagram of cable *G* and figure 7 of cable *H*.

Discussion of Results

Among the 26 samples tested in Detroit, *A*1, *A*2, *I*1, and *J*1 were single conductor, solid type cables, each having a standard stranded, round, copper conductor. Since the taping and impregnation were approximately the same for the four samples, they offer a basis for comparison of geometrically different constructions. Tabulating the average stresses at breakdown discloses a ratio of 1.43 between maximum and minimum values. Calculating on the basis of maximum stresses after correcting for stranding, yields a ratio of 1.11. This is clearly an indication that maximum rather than average stresses determine the breakdown voltage.

Further indication of the correctness of this theory is obtained in considering another group of three cables of equal insulation characteristics, namely samples *E*4, *F*1, and *F*2. Both cables from which these samples were taken had the same insulation thickness, uniform taping, and high degree of impregnation, but cable *F* had a conductor diameter very much larger than that of cable *E*. The ratio of average stresses of cables *E* and *F* was 1.2 in favor of cable *F*. The ratio of maximum stresses is, on the other hand, 1.01.

Having considered two different groups of cables separately, comparison of the two groups in relation to each other will now be made. The maximum stresses of the first group vary from 2,660 to 2,980 volts per mil, whereas the corresponding values for the second group are 3,250 to 3,450 volts per mil, the averages of the two groups being 1.21. Visual examination of the samples indicated that those in the first group exhibited a lesser uniformity of taping and a lower degree of impregnation than samples in the second group. Thus it can be concluded that the maximum stress, which has been shown to be independent of the geometry of the construction, depends solely upon the quality of the insulation, as measured by the uniformity of taping and the degree of impregnation.

Further and more specific proofs of this statement are supplied by results of tests on other groups of cables. The influence of taping and that of impregnation will be considered in separate paragraphs.

The best evidence in regard to the influence of the quality of taping on the impulse strength of cables was supplied when samples *G*1, *G*2, *H*1, and *H*2 were tested and examined. The cables from which these samples were taken, were identical in dimensions and, both being oil-filled, possessed the same high degree of impregnation. The samples differed from each other in only one respect, i.e. in the degree of uniformity of taping which again was manifested in much lower maximum stress at breakdown (23 percent) for the samples with inferior taping.

The importance of the degree of impregnation without the disturbing influence of variations in taping is demonstrated when the results of tests on the low gas-pressure cable, samples *B*1 to *B*6, are examined and compared with the results of tests on a well-impregnated solid-type cable, samples *C*1 to *C*3. Both types of cables contained sector shaped conductors having nearly equal minimum radii (167 and 151 mils, respectively) at the "shoulders," "compack" stranding was employed, producing approximately equally smooth surfaces; and the taping was equally uniform. The less complete impregnation in the low gas-pressure samples, therefore, appears to be responsible for the 15 percent decrease in maximum stresses.

The smoothness of the electrode surface has for some time been known to influence the impulse flash-over values in gases and liquids. How much practical importance should be attached to smoothing of the conductor surface in cables is indicated by comparing samples *C*1 to *C*3 ("compack" stranded) to samples *D*1 to

Table II

No.	Tested by	Type of Cable	r.	w.	R.	n.	Breakdown Volt. Kv	G. Avg. V/Mil	G. Max. V/Mil
1–5	Foust and Scott	Solid	210	187	397	12	350	1,870	3,330
6							375	2,005	3,570
7							400	2,140	3,800
8	Foust and Scott	Oil-filled	945	315	1,260	48	610	1,935	2,895
9							512	1,625	2,430
10							448	1,420	2,120
11							453	1,440	2,150
12							461	1,465	2,180
13	Foust and Scott	Oil-filled	945	500	1,445	48	500	1,590	2,370
14							490	1,555	2,320
15							555	1,760	2,630
16							559	1,775	2,650
17							559	1,775	2,650
18							730	1,460	2,360
19	Foust and Scott	Oil-filled	945	500	1,445	48	765	1,530	2,475
20							630	1,260	2,035
21							648	1,295	2,090
22	Foust and Scott	Oil-filled	515	500	1,015	25	902	1,805	3,345
23							928	1,855	3,440
24							940	1,880	3,485
25	Foust and Scott	Oil-filled	515	600	1,115	25	1,067	1,775	3,485
26							1,104	1,840	3,605
27							1,115	1,860	3,640
28							856	1,425	2,795
29							916	1,525	2,990
30							836	1,395	2,730
31							896	1,495	2,925
32							940	1,565	3,070
33							1,014	1,600	3,310
34	Davis and Eddy	Solid	81	94	175	Solid	188	2,000	3,030
35	Held and Leichsenring	Solid	349	118	467	Smooth surf.	280	2,370	2,745
36		Oil-filled	349	118	467		284	2,410	2,785
37		Solid	349	236	585		484	2,050	2,690
38		Oil-filled	349	236	585		510	2,160	2,830
39		Solid	349	472	821		809	1,710	2,715
40		Oil-filled	323	531	854		940	1,770	2,990

r. Minimum radius of conductor, mils.
w. Thickness of insulation.
R. Minimum radius over insulation.
n. Number of strands in outer layer.

*D*3 (strand shielded with semi-conducting tapes). The smoothness of the conductor surface in these samples increased the breakdown voltage by an average of 24 percent. In assessing the significance of this increase, the reduced effective insulation thickness in cable *D*, owing to the substitution of semi-conducting tapes for insulating tapes, near the electrodes, should be taken into account. With an equal thickness of effective insulation, this value would be nearer 30 percent.

The application of 200 psi pressure, gas or oil had a rather curious effect on the maximum stress at breakdown (samples *E*1 to *E*4). It was expected that pressure would increase the impulse strength. On the contrary the results indicated a ten percent decrease due to pressure. If the lower value had been found in only one specimen and the higher value in several specimens, the results might be ascribed to local conditions. However, the single specimen (sample *E*4) tested without pressure was found to have the highest value. Further investigation is recommended before final conclusions are drawn as to the effect of pressure on impulse strength.

Conclusions

The results of the impulse tests conducted by The Detroit Edison Company on various types of impregnated paper-insulated cables seem to indicate that with the type of impulse wave and method of application used in these tests, in a cable having the best obtainable insulation, breakdown occurs at a voltage for which the maximum stress is around 3,300 volts per mil. For a given insulation thickness, therefore, an increase in the minimum radius of the conductor and the use of smoother electrode surface should result in an increase in breakdown voltage. If the quality of the insulation is inferior, owing either to non-uniformity of taping or incomplete impregnation, or both, the maximum stress value can be expected to become less than 3,300 volts per mil. Therefore, the maximum stress obtained from impulse tests, compared with 3,300 volts per mil is a good measure of the uniformity of taping and the degree of impregnation of the insulation. The correlation obtained in these tests between the impulse strength value and the findings of visual examination, such as those shown in Mildner diagrams (also styrene wafers), shows that these visual tests in their turn can justifiably be used as a measure of the impulse strength of the cable insulation.

In view of the above mentioned results, solid, oilfilled, oilostatic, and compression cables should all have the same maximum stress at breakdown. For a given insulation thickness and conductor surface, the oilfilled cable, therefore, having the advantage of an intrinsically large diameter of the conductor will withstand the highest voltage before breakdown occurs.

The tests also indicated that this type of cable will retain this advantage even after aging. The solid, oilostatic, and compression cables, when new, belong to the same group as regards impulse strength. From the decrease of the degree of impregnation in service, it is logical to assume that service aged solid cables have a lower impulse strength than new ones and this assumption is borne out by test. By inference, it may be concluded that the care used in taping solid type cables is more important than the degree of impregnation since age decreases the beneficial effect of the latter, whereas the former will remain practically the same. Oilostatic and compression cables, on the other hand, can be expected to retain their original breakdown values even after aging, although there is as yet no direct experimental verification of this assumption. Low gas-pressure cables, although originally lower than solid-type cables as to impulse strength, are expected to retain this value after service aging and it is possible that they would then show even higher impulse strength than solid-type cables.

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Appendix

1. In case of a cylindrical concentric cable with smooth surfaces of conductor and sheath, the field stress (*S*) at a point of the dielectric is given by the equation

$$S = \frac{E}{r_1 \log \frac{R}{r}} \quad \frac{\text{volts}}{\text{cm}} \qquad (1)$$

where

E = voltage applied between conductor and sheath

The A-C Dielectric-Loss and Power-Factor Method for Field Investigation of Electrical Insulation

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General

THE use of dielectric loss and power factor for testing the insulation of electrical equipment in service position in the field with one side grounded began with the advent of the apparatus and method described in this paper.

Through its use, tables of standard values have been set up indicating when insulation is "good" for continued operation with an adequate factor of safety or when it is "bad" to a degree that warrants investigation and possible replacement in order to insure continuity of service until the next scheduled test.

Types of insulation that were being discarded as inherently bad, judged by their high failure record, now are being re-established as good insulation after the tests have shown the defects to be largely of a secondary nature and removable or curable.

History

A series of high-voltage bushing failures occurring about 1925 emphasized the need for developing a practical field test for this type of insulation that would indicate the presence of certain types of fault or deterioration which inherently were not detectable by a non-destructive direct-current test.

A considerable amount of research and development work was done and several methods were tried and discarded before the ultimate discovery of the a-c dielectric-loss and power-factor method.

The voltage-distribution method for testing high-voltage live-line insulators which had been in successful use for several years was first tried but this method failed to reveal many types of defective insulation that were responsible for costly service interruptions.

Apparatus was then developed for measuring the charging current of a bushing at operating line voltage by isolating on an insulating support a current instrument arranged for connection in series between the terminal of the bushing and the live line normally leading to it. This test did not reveal certain types of defects in insulation and service interruptions continued to occur.

Finally the method described in this paper was devised in which voltamperes, watts, and the power factor of the insulation were measured in the field with portable instruments. The operation and application of the apparatus during the past ten years have been described in the papers listed in the bibliography. This paper is concerned with the technical electrical features and principles involved. There are different forms in which the apparatus may be constructed. For the purpose of discussion, the details of one form of the apparatus will be used to illustrate the general principles.

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1. For all numbered references, see list at end of paper.

Test Apparatus Elements

The elements of apparatus required in an a-c dielectric loss method for field investigation of electrical insulation are shown in figure 1.

A 110-volt supply feeds a step-up transformer, T.

From the high-voltage terminal of the high-voltage winding, a cable connection leads to one side of the specimen, $C_x R_x$, which is grounded.

The measuring means, M, is connected between one side of the high-voltage winding of the transformer, T, and the grounded specimen under test.

Technical Problems

There are special technical problems involved in apparatus designed to measure losses in insulation as installed in the field with one side permanently grounded and subject to electrostatic induction from adjacent or surrounding circuits and apparatus. Because the ground connection can-

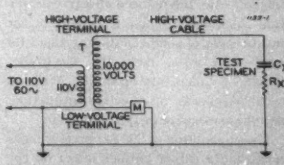

Figure 1. Apparatus to measure a-c dielectric loss in grounded insulation

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r_1 = radial distance of the point from the center of the cable
r = inner radius of insulation
R = outer radius of insulation

Maximum stress for a given cable will be at the surface of the conductor when $r_1 = r$ and the equation will be

$$S = \frac{E}{r \log \frac{R}{r}} \qquad (2)$$

2. For sector shaped conductors with paralleling ground (shielded cable), and smooth surface of conductor and shielding, the portion of the sector containing the points with the greatest stress, is what is known as the "shoulder" of the sector, having the minimum radius of curvature. In cables with sector-shaped conductors maximum stress was estimated by substituting these minimum radii in equation 2.

3. For elliptical (oval shaped) conductors same consideration as in 2, was applied.

4. To calculate the effect of stranding in cables other than those with compacted stranding, the following formula developed by Serguis Vesselowsky of The Detroit Edison Company was used:

$$S = \frac{0.572nE}{r\left(0.119 + n \log_{10} \frac{R}{r}\right)} \qquad (3)$$

where

n = number of strands in outer layer
E = voltage applied between conductor and sheath
r = inner radius of insulation
R = outer radius of insulation

Above formula appears to be sufficiently accurate for high values for n (greater than 6).

5. In case of compacted stranding, the maximum value should be somewhat higher than that found in similar cable with smooth conductor surface. However this type of conductor does not lend itself to ready calculations because of differences of smoothness of conductor surface.

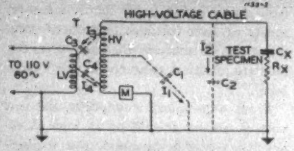


Figure 2. Simplified circuit diagram showing charging currents originating in the test apparatus itself

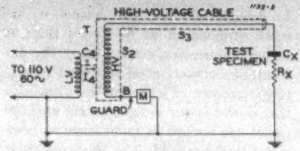


Figure 3. Test circuit diagram with shields to divert I_1, I_2, I_3

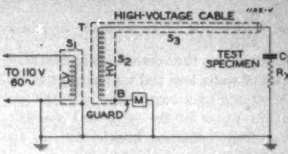


Figure 4. Test circuit diagram with shields to divert I_1, I_2, I_3, I_4

not be removed or even temporarily disconnected, the measuring means cannot be connected between the specimen and ground, and so cannot be connected directly in series with the insulation it is desired to measure. Consequently, the permanent ground limitation may cause the measuring apparatus to be subjected to electrical influences other than the losses in the insulation. For example, there may be:

Charging currents originating in the measuring apparatus itself.

Changes in phase angle and current caused by variations in capacitance.

Effects from extraneous electric fields.

Charging Currents Originating in the Apparatus Itself

In figure 2 the charging currents originating in the apparatus itself are indicated on a simplified diagram of the test equipment without any shielding. The distributed capacitance between the high-voltage winding of the transformer and ground is represented by a single capacitance, C_1, and the resulting charging currents are represented by I_1. The distributed capacitance which extends the entire length of the high-voltage cable is shown conventionally as a single capacitance, C_2, and the charging current as I_2. The distributed capacitance and current from the high-voltage end of the 10,000-volt coil of the transformer are shown as C_3 and I_3. Likewise the distributed capacitance and current between the 110-volt coil and the low-voltage end of the 10,000-volt winding are shown as C_4 and I_4. All of these charging currents, I_1, I_2, I_3, and I_4, flow through the measuring means, M, in addition to the current through the specimen which alone it is desired to measure. It is realized that these currents involve both capacitance and loss components but for brevity they are referred to as charging currents.

In figure 3 there have been added to the circuit of figure 2 guard shields S_2 and S_3 around the high-voltage winding of the transformer and the high-voltage lead. Charging currents I_1, I_2, and I_3 are diverted from the measuring means, M, by these shields, but I_4 continues to flow through M.

In figure 4 there has been added to the circuit of figure 3 a grounded shield S_1 around the low-voltage winding of the test transformer. This shield, S_1, diverts charging current, I_4, from the measuring means, M. This is important because the phase displacement of I_4 may be such that it will cause large errors in the watts measurement.

Changes in Phase Angle and Current Caused by Variations in Capacitance and Effects From Extraneous Electric Fields

From a study of figures 3 and 4, it is obvious that the capacitance between ground and the shields S_2 and S_3 is in parallel with the measuring means, M. This capacitance shunt diverts some of the test specimen current away from M. Correction for this shunting effect can be made by means of a compensating circuit or network. If this shunting capacitance is kept substantially constant, need for adjusting the network is practically eliminated. One method for maintaining constant capacitance is shown in figure 5 where, in addition to the shields S_1, S_2, and S_3 there are grounded shields S_4 and S_5 which surround the guard shields S_3 and S_2 on the high-voltage cable and the apparatus. Means for compensating the shunting effect are provided by the adjustable network R and C.

An additional function of the grounded shields S_4 and S_5 is to prevent currents induced from extraneous sources from flowing through the measuring means. By reference to figures 3 and 4, it will be seen that currents induced in the shields S_2 and S_3 from extraneous sources, such as adjacent high-voltage circuits, would flow to ground through the measuring means, M, thus vitiating the measurement. The shields S_4 and S_5 conduct such currents directly to ground.

This grounded shielding also contributes greatly to the safety of the operator by providing a direct path to ground for stray currents due to accidental breakdown of the insulation of the test circuit or contact with external high-voltage sources. In actual practice, lives of operators have been saved by this ground shielding when defective operating mechanism caused bushings under test to be accidentally alive at line voltages.

Even with the test apparatus and the test cable protected from external fields, the bushing or other test specimen may be so positioned as to have a considerable voltage induced at its high-voltage terminal due to extraneous sources. Voltage so induced in the specimen may in turn produce currents to ground which will flow through the measuring instruments, and it is essential to have means in the set itself for making corrections for these effects. A reversing switch, SW (figure 5), performs this function.

In practice, if the test voltage is less than 90 degrees out of phase with the current induced in the test specimen due to external fields, the resultant current and watts, as determined by the instruments, will be too great. If, however, the phase of the induced current is more than 90 degrees out of phase with the test potential, the watts and current indicated on the instruments will be too small. The actual value of watts loss in the insulation under test may be determined by taking two readings, first with the reversing switch in one position and then in the other. The algebraic average of these two readings is the actual watts loss in the specimen, and the algebraic average of the current is substantially the current flowing through the test specimen due to the test voltage. Thus, power factor can be calculated from watts-loss and current values determined under severe conditions of interference.

For example, let W_1 and W_2 be the observed values on the wattmeter, and I_1 and I_2 be the current readings, with the reversing switch first in one position and then in the other. The algebraic average of the watts loss will be $\frac{W_1+W_2}{2}$, and the algebraic average of the current will be $\frac{I_1+I_2}{2}$.* The resulting power factor will

* In practical application it is found that the current from induced voltages is small in comparison with the current through the specimen due to the test voltage, and hence its effect on the phase of the test current may be disregarded.

be $\frac{W_1+W_2}{E(I_1+I_2)}$. The accuracy of power-factor values thus derived from field readings of watts loss and voltamperes is well illustrated by a comparison with the true power factor of the same test specimen free from induction interference, as follows:

Observed values in the field:

$E = 10{,}000$ volts
$W_1 = 1.9$ watts
$W_2 = -1.6$ watts
$I_1 = 895$ microamperes
$I_2 = 685$ microamperes

The formula $\frac{W_1+W_2}{E(I_1+I_2)} =$

$\frac{1.9+(-1.6)}{10{,}000(895+685)10^{-6}} = 1.9\%$ power factor

True power factor, no induction $= 2.0\%$.

In passing it is interesting to note that it is not possible to compute the correct power factor by averaging power factors obtained under conditions of electrostatic interference by direct and reversed connections of the test voltage respectively. The algebraic expression for averaging power factor would be $\frac{\frac{W_1}{EI_1}+\frac{W_2}{EI_2}}{2}$, which equals $\frac{W_1I_2+W_2I_1}{2EI_1I_2}$. Applying this formula to the example cited above gives:

$$\frac{1.9(685)(10^{-6})+(-1.6)(895)(10^{-6})}{20{,}000(895\times10^{-6})(685\times10^{-6})} = -1.1\% \text{ power factor}$$

which negative result obviously is incorrect and in this case meaningless.

Test Frequency—60 Cycles

A test frequency of 60 cycles is most desirable because, other things being equal, a test at normal operating frequency reflects actual operating conditions. Moreover, the power factors due to defects in composite insulation are more pronounced at 60 cycles than at higher frequencies, consequently the differential between good and bad insulation is greater. Field trials have revealed that power-factor measurements at 1,000 cycles are limited in their scope as compared to 60 cycles.[5] The thousand-cycle power-factor test proved inadequate to indicate types of serious deterioration which were readily found by the 60-cycle power-factor test.

Test Voltage

A successful field testing apparatus requires a test potential adequate to detect deterioration in insulation of all voltage ratings up to and including the highest kv rating in practical use, which at the present time is 287 kv.

In practice, the operating company is interested principally when insulation has deteriorated to a point where it has become a failure hazard or represents a radio interference problem.

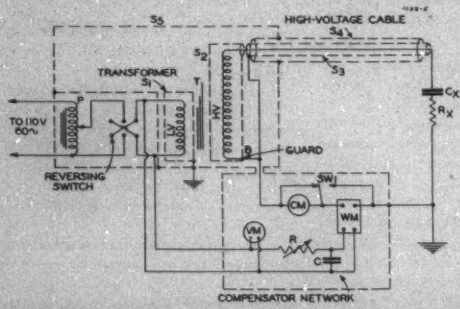


Figure 5. Simplified diagram of the watts-loss and power-factor tester

From a design standpoint the manufacturer is interested also to learn of inherent defects or incipient faults which may ultimately cause deterioration even though the resulting destruction of insulation value may not represent an electrical failure hazard until after many years of service operation.

Considering specifically the manufacturers' interest in new design, a test potential equal to or higher than operating voltage might furnish valuable data if it were possible in the field to separate the true loss from abnormal losses due to corona and extraneous interference conditions. However, except for studies of new design the advantages to be derived by the use of over-voltage in routine field testing are heavily outweighed by its obvious disadvantages. Extensive investigation of bushing insulation in the field showed that power-factor measurements at over-voltages introduced complications of analysis that are of no immediate practical value to the power company.

From a technical standpoint, the test voltage chosen should be as high as efficiently possible to meet the requirements of surface contact difficulties, ample unit stress on the insulation under test, and the minimizing of extraneous influences. On the other hand, the difficulties of segregating corona losses from insulation losses and the problems of portability, power supply, and regulation (all of which increase with voltage) compel a compromise in the interest of economy and efficiency. Tests at 10 kv appear to avoid a maximum of the difficulties. Data from ten years' experience with field tests on insulation rated from 10 kv to 287 kv indicate that a 10-kv test potential is adequate to solve the operating maintenance problem and also to make contributions useful to the manufacturer in his design problems.

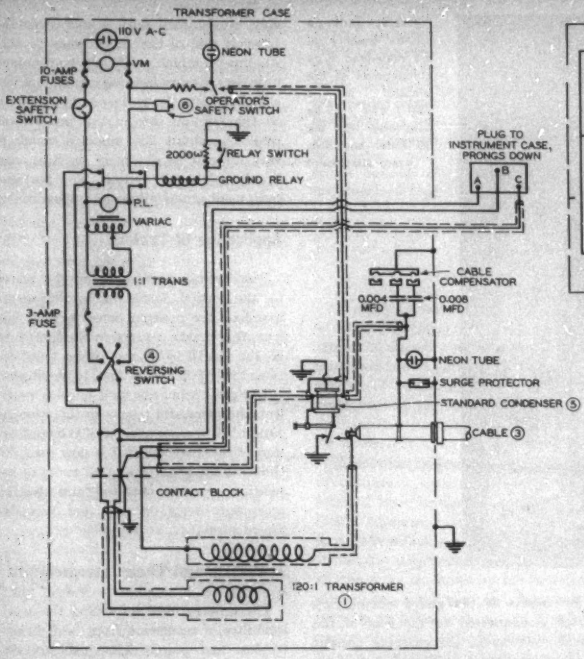
Collar Tests

Need for localized high-voltage stress under special conditions, such as occur in voids in compound-filled bushings, is met by applying a metal band or "collar" to critical parts of the insulation so that the application of 10 kv produces higher unit stress at these local parts than would be produced by a test at full line voltage on the insulation as a whole. For example, tests at 10 kv impressed on metal collars placed under the first or second petticoat of a bushing will produce stresses that will indicate the presence of moisture, voids, and other abnormal and deleterious conditions in their incipient stages. In testing compound-filled bushings, the power-factor measurement is almost universally supplemented by the collar test. The trend of both measurements is carefully tabulated from consecutive tests and both are taken into consideration in the final analysis of the bushing condition.

Test Apparatus Details

In the particular circuit illustrated by figure 5, it will be noted that the measuring means consist of a voltmeter, wattmeter, and current instrument. In the following description (to differentiate this set from other types of measuring equipment which could be used), this equipment will be referred to as the "watts loss and power factor apparatus."

Figure 6 is a wiring diagram of a complete watts loss and power factor insulation test set, shown pictorially in figure 7.



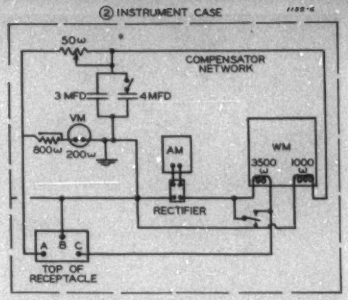


Figure 6. Watts-loss and power-factor tester

The set comprises:

1. Shielded step-up test transformer as a test voltage supply (120:1 trans.).
2. Shielded set of measuring instruments (voltmeter, ammeter, wattmeter in instrument case).
3. Multi-shielded cable for connection to the specimen under test.
4. Reversing switch.
5. Standard capacitor.
6. Safety relay and switches.

The test voltage supply is a 120:1 ratio, 13,200-volt, 60-cycle potential transformer capable of delivering 150 milliamperes at 10 kv.

The shielded set of measuring instruments includes:

A voltmeter calibrated for a range from 0 to 12.5 kv.

An ammeter having four scales, calibrated to cover a range from 0 to 10,000 microamperes.

A wattmeter of special dynamometer type having two scales with ranges of 0 to 2.4 and 0 to 12.0 watts. (Actual sensitivity of the wattmeter: 0.02 watt full scale.)

The multi-shielded cable has four concentric conductors separated by graded insulations of 500 volts, 10,000 volts, and 500 volts, respectively.

Figure 7. Watts-loss and power-factor tester assembled for use

Safety

Important safety features shown in the circuit diagram include a protective relay, series switches, and a safety grounded shielding system surrounding the entire test apparatus including the high-voltage test cable except a hook at the end for contact with the test specimen. Danger from contact with the test voltage is practically eliminated since the hook is the only exposed live part. The arrangement of the shielding is particularly effective in protecting the test operator against trouble arising outside the test apparatus itself, such as the remote but extremely dangerous possibility of accidental direct contact of the hook with the live line, or possible abnormal conditions due to serious voltages induced in the test circuit by short-circuit or ground occurring in neighboring equipment.

Range of Test Apparatus

The testing range of the apparatus described in this paper is from 0 to 2,000 milliamperes, or 2 amperes, at 10 kv.

To meet more special testing conditions, the apparatus has been adapted to convenient ranges of 10, 30, 150, and 2,000 milliamperes. The larger ratings are used for testing power transformers and cables. The design and physical dimensions of the apparatus are substan-

Figure 8. Testing a 220-kv bushing of the draw-lead type independent of the winding in a 220 / 110 / 13-kv transformer with the 30 tester and hot-guard attachment

tially the same up to and including 150 milliamperes, beyond which range additional equipment is required.

Auxiliary Test Equipment

For special tests a shielded current transformer, called "hot guard" transformer, is used in combination with regular testers. For example: in addition to making an overall test on a power transformer, it is advantageous to be able to test the transformer bushings individually without disconnecting the windings at the lower end of the bushing under oil. For this purpose, when the transformer winding terminates in a draw lead through the bushing, a "hot guard" attachment is used to supplement the regular test equipment. Figures 8 and 9 show a set with the "hot guard" attachment arranged for making tests on a transformer bushing in a 23,000-kva transformer. In this apparatus, a shielded current transformer, *CT*, is inserted in series with the high-voltage lead so that transformer bushings of the draw-lead type readily can be measured independently of the transformer winding. The test voltage is applied between the metal tube electrode *A* and ground and only current flowing from this electrode *A*, through the insulation of the bushing, to ground actuates the measuring instruments by flowing through the transformer primary, *W*.

By means of the guard circuit S_6S_7 which is connected to the lead of the transformer at *L*, the charging current flowing into the winding of the transformer through the capacitance *CW* to ground is by-passed from the measuring instruments. The wiring diagram of the "hot guard" test set as adapted to testing transformer bushings is shown in figure 9. It will be noted that the guard circuit, S_6S_7, which by-passes the current transformer winding is at nearly the same potential as that applied to the specimen. Thus, for test purposes, the insulation between the draw lead and the bushing tube need be only sufficient to withstand low voltage. In the test cable already described in connection with figure 6, the concentric (hot guard) shield nearest the center conductor is provided for this special test, and during a "hot-guard" test another shield, called the cold-guard shield, is connected to ground.

For testing generators and cables requiring charging currents up to 2 amperes at 10,000 volts, a shielded resonating choke is connected directly across the high-voltage winding of the test transformer and adjusted until the inductance of the choke and the capacitance of the test specimen are anti-resonant at 60 cycles. Under this condition the test transformer is required to supply only the losses in the choke-specimen resonant system, and 2 amperes at 10,000 volts may be obtained with a supply to the 110-volt side of the transformer of only 20 amperes which easily can be obtained from an ordinary lighting circuit. Without the choke the corresponding current on the 110-volt side of the transformer would be about 200 amperes which is very difficult to obtain in practice, and its complete regulation by portable equipment practically is an impossibility.

Application of Tester

The technique of applying the tester to the varied forms of insulation as found on the modern power system has been thoroughly covered in the literature of the AIEE,[1,2,3,4] and other publications,[5,7,8,10,11] listed in the bibliography.

Designed primarily for a bushing problem, the successful results in this investigation led to an extension of the application of the tester until it is now used for checking the condition of all types of insulation in service position, and also for acceptance tests on new and reconditioned insulating structures.[1,2,3,4]

Test Data and Their Interpretation

The criteria used for rating the serviceability of insulation from field dielectric-loss and power-factor tests are derived from the correlation of thousands of field tests, and many investigations. They are based on certain well known facts about insulation.

The correct interpretation of field dielectric-loss tests requires a knowledge of the detailed construction of the apparatus being tested and the characteristics of the particular types of insulation used. For example, each type of bushing has certain characteristics peculiar to its construction; defective internal insulation of an oil circuit breaker shows up in different ways depending upon the breaker construction.

The dry type porcelain bushing is subject to corona formation which must be considered in analyzing the test data. The condenser type bushing may show a normal power factor but have several condenser layers shorted out; this is revealed by an increase in charging current (capacitance) during the routine dielectric-loss test. A decrease in charging current for some types of compound-filled bushings indicates a break in the ground shield connection. The oil-filled type bushing may have a high power factor as a result of deteriorated oil; if the oil is replaced promptly, there may be no injurious after-effects. Collar tests will reveal defects in compound-

embedded bushings that otherwise would be masked.

The condition of the internal insulation of an oil circuit breaker is revealed by a comparison of the sum of the watts loss for the two bushings in a tank during the open-breaker test, with the combined loss of these same two bushings during the closed-breaker test. A study of these data will indicate defective lift rods or flash barriers, defective cross braces, wet or dirty de-ion grids, and many other forms of operating hazards.

No piece of insulation should be condemned until it has been completely isolated, cleaned, and compensated for temperature. Experience has shown that approximately two-thirds of the cases of high over-all dielectric loss initially found are due to bad operating condition such as carbon deposit, etc., that can be removed by ordinary servicing.

Standards for evaluation of test results appear in the literature,[2,3,4,7,9,11] as well as voluminous data concerning the results of their application to the insulation tests of typical operating companies.[1,2,3,4,5,7,9,10,11]

Typical test results[2] have indicated that defective equipment testing high enough to be removed from service is distributed among various types of apparatus in the following order:

	Percentage in "Remove" Class
Oil circuit breaker bushings	2.1
Oil circuit breaker tank faults	1.6
Transformer bushings	3.2 to 3.9
Spare bushings	8.8
Instrument transformer windings	7.7
Power transformer windings	3.1

By the use of the technique and apparatus described, defective insulation can be detected in time for removal from service before it fails.[1,2,3,4,5,7,9,11] Such anticipation of failures not only prevents service interruptions but also makes possible the rehabilitation of defective insulation which otherwise might have been destroyed.

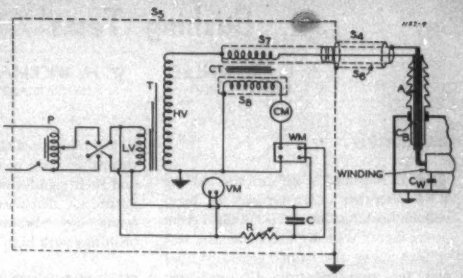


Figure 9. Schematic diagram of the essential portions of the tester circuit when the shielded current transformer "hot guard" is employed for testing transformer bushings of the draw-lead type

Of a large number of bushings tested and indicated defective to a point needing attention, about one-half of the faults were found to be external to the main insulation of the bushing and a considerable percentage of the faults that are in the main insulation can be cured or improved by servicing.[7]

"Insulation faults develop in all types of equipment such as bushings, transformers, wood insulation, and oil regardless of equipment design as it exists today. These faults may develop critically within test period intervals of 18 months to two years, as shown by the experience cited above, and appear, in a few cases, to develop to a lesser degree in a shorter period of time. Periodic testing, therefore, is necessary if a high standard of insulation is to be maintained."[2]

Conclusions

The use of the apparatus and method described in this paper makes it possible successfully to measure the a-c dielectric loss and power factor of all types of high-voltage insulation in service position. Such measurements provide an adequate non-destructive method for economical maintenance of insulation and for detecting deterioration in time to prevent failure.[4] The use of the equipment for tests at regular intervals and proper interpretation of the results will reduce to a minimum service interruptions due to faulty insulation.[3] Experience has proved that the period between tests of equipment in important locations should not exceed one year.[4]

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Bushing Tests

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Introduction

MORE complete information on the dielectric characteristics of high-voltage bushings has been obtained from power-factor tests by extending the test voltage above the values generally used and by supplementing the ordinary power-factor tests with laboratory examinations of deteriorated bushings.

Most power-factor tests on high-voltage bushings have been made at a relatively low voltage, about 10 kv, regardless of the operating voltage of the bushing. These tests have been valuable in determining the general condition of the insulation. But by extending the test voltage to higher values, even above the operating voltage, it has been possible to detect defects in new bushings which would shorten their useful life and to detect certain types of deterioration in older bushings, both of such a nature that they are not shown by a low-voltage test.

Laboratory examinations of deteriorated bushings have been valuable in determining the nature, extent, and cause of bushing deterioration. Such information is needed to properly evaluate power-factor test results.

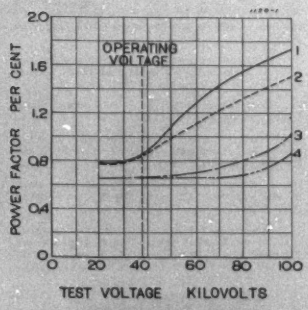

Figure 1. Power factor versus voltage curves, 66-kv condenser-type bushings

The purpose of this paper is to give the results of tests made at higher voltages and their significance and to describe the nature of deterioration in bushings as found by laboratory examinations of bushings with high power factor.

High-Voltage Power-Factor Tests

Power-factor tests on bushings at voltages equal to or above the operating voltage have shown defects in new bushings which would not have been found by a low-voltage test.

Ionization in two new 66-kv condenser-type bushings at a voltage below their operating voltage is shown by the sharply rising power-factor vs. voltage curves No. 1 and 2 in figure 1. Curves No. 3 and 4, taken on similar bushings, are given for comparison and show satisfactory power-factor-voltage characteristics. Curves 1 and 2 show an abnormal increase in power factor with voltage. Corona was present within these bushings at their normal operating voltage, 38 kv, as indicated by the breaks in the curves below that point. The ionization probably occurred in voids in the insulation which may be formed by wrinkles made in wrapping the paper which forms the condenser layers. The photograph of figure 2 shows a condenser-type bushing which was dissected and showed such wrinkles.

Corona has a deleterious effect on the insulation. Discoloration of the insulation around voids has been found in bushings which have been dissected. The action of corona will, in time, produce weak spots in the insulation and might lead to ultimate failure. New bushings in which corona is present at the operating voltage, as shown by high-voltage power-factor tests, are not acceptable.

Power-factor tests at these higher voltages have also shown up deterioration in older bushings which would not have been found by a low-voltage test.

The partial failure of a 44-kv condenser-type bushing is shown by the power-factor and capacitance vs. voltage curves of figure 3. The increasing power factor with increasing voltage, together with the abrupt change in capacitance above 60 kv indicate that the insulation of one of the condenser layers was deteriorated so that it became partially conducting at the higher voltages. This was confirmed by measurements on the individual layers as given in table I. The outer layer had a very high power factor, 29.6%, compared with an average of 1.65% on the inner seven layers. The high power factor of the outer layer was found to be confined to the area under the ground flange as shown by the curve of figure 4 which gives the power-factor variation longitudinally over the outer layer. The insulation of this outer layer had become contaminated with glycerine from the litharge and glycerine cement used in cementing the ground flange to the condenser.

Partial failure of an oil-filled bushing is shown by the power-factor and capacitance vs. voltage curves of figure 5. While the fault had progressed so far that the power factor was high even at the initial voltage of 10 kv the increasing capacitance with increasing voltage and the changing power factor indicate the nature of the fault—a carbonized path within the bushing. The lower ends of the four inner insulating barriers between the conductor and the equalizing shield were badly burned and heavily carbonized. This conducting path gave rise to the high power factor and to the changing characteristics with increasing voltage.

Laboratory Examinations

Laboratory examinations have been useful in determining the penetration of moisture in bushing insulation and the effectiveness of drying methods. Figure 6 shows a sketch of a 66-kv condenser-type bushing which had a high power factor due to moisture absorption and table II gives the results of the examinations made to determine the distribution of moisture in the insulation and the effectiveness of drying. The power factor of this bushing was not reduced by drying at atmospheric pressure; on the contrary,

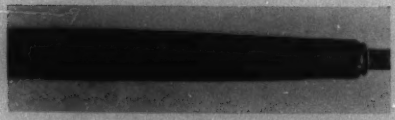

Figure 2. Condenser-type bushing with outer layers of insulation removed

Wrinkled paper at the lower end of the section (left) shows how voids may be formed, in which ionization occurs

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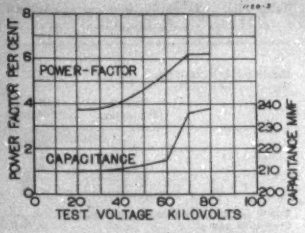

Figure 3. Power factor and capacitance versus voltage curves, 44-kv condenser-type bushing

it increased slightly. Moisture had entered the top of the bushing. This was confirmed by separating the ground wire into two sections, *A* and *B* of figure 6, and measuring the power factor to the upper and lower parts. The power factor was higher under the upper part, *A*. Further drying reduced the power factor somewhat because the separation of the outer layer between *A* and *B* afforded the moisture a means of escape. By measurements on the condenser layers it was established that moisture had penetrated to the second outer layer and that the inner eight layers had not been affected. Also, after prolonged drying at atmospheric pressure the second outer layer still contained a considerable amount of moisture.

Drying under vacuum has been much more effective in reducing high power factors caused by moisture. The curves of figure 7 show the results of drying four condenser-type bushings in vacuum The power factors of all four were reduced to

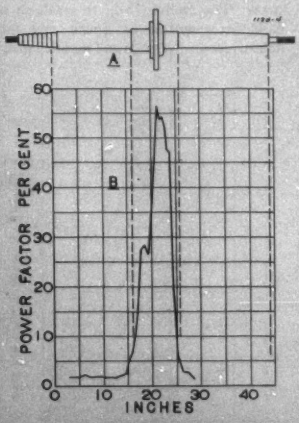

Figure 4. (A) Sketch of 44-kv condenser-type bushing; (B) power factor of outer layer

Table I. 44-Kv Condenser-Type Bushing, Power Factor of Condenser Layers

Layer No.	P.F. %
1	1.83
2	1.81
3	1.77
4	1.61
5	1.44
6	1.21
7	1.88
8	29.6

NOTE: The layers are numbered from the conductor outward.

satisfactory limits in reasonable time.

While moisture has generally been considered the chief cause of high power factor in bushings, laboratory examinations have also shown contamination from substances other than moisture.

In the 25-kv solid-type bushing sketched in figure 8*A*, the impregnated paper had been contaminated by acid compounds formed by deterioration of the varnished cloth. The variation of power factor longitudinally is shown in figure 8*B*, curve 1. The power factor was highest in the area under the ground shield. Curve 2 was taken after removing 0.2″ of the outer paper and curve 3 after removing 0.1″ more. A comparison of these curves shows that the power factor was highest n the outer part of the impregnated paper which was nearest the varnished cloth.

In a 37-kv solid-type bushing shown in the photograph of figure 9, the impregnated paper had been contaminated with a mixture of oil and filling compound. The power factor of this bushing was 9%.

Table II. Power-Factor Test Results on 66-Kv Condenser-Type Bushing of Figure 6

1. Bushing as received	Conductor to 10		3.8%
2. After drying in air for 8 days at 90 deg C.	Conductor to 10		3.9%
3. After drying in air for 12 days at 110 deg C. With section of ground wire and outer insulation removed at *C*, figure 6.	Conductor to 10		4.1%
4. After drying in air for 11 more days at 110 deg C	Conductor to 10*A*		9.4%
	Conductor to 10*B*		3.0%
	Conductor to 10*A*		3.4%
	Conductor to 10*B*		2.3%
	Conductor to 1		1.3%
	1 to 2		1.2%
	2 to 3		1.0%
	3 to 4		1.0%
	4 to 5		1.0%
	5 to 6		1.5%
	6 to 7		1.1%
	7 to 8		1.9%
	8 to 9		24.0%
	9 to 10*A*		7.0%
	9 to 10*B*		4.1%
	Conductor to 9		2.2%
	Conductor to 8		0.7%

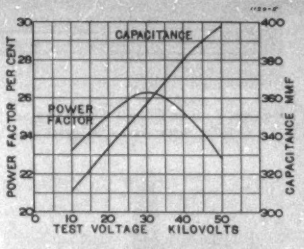

Figure 5. Power factor and capacitance versus voltage curves, oil-filled bushing

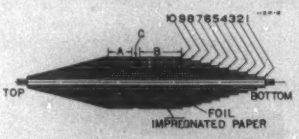

Figure 6. Sketch of 66-kv condenser-type bushing

Power-factor test results are given in table II

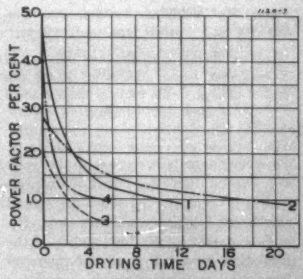

Figure 7. Vacuum drying of condenser-type bushings

Curves showing power factor versus drying time

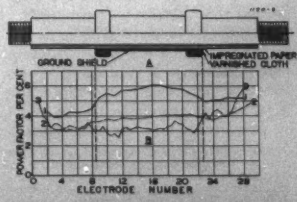

Figure 8. (A) Sketch of 25-kv solid-type bushing; (B) Power factor of impregnated paper

(1) Full thickness, 0.375 inch
(2) Turned down to 0.175 inch
(3) Turned down to 0.075 inch

Figure 9. Solid-type bushing with section of insulation removed to show contamination

The path of oil up through the bushing can be seen at the lower end (left). The dark portion in the center shows the penetration of dissolved filling compound from the top

Figure 10. Oil-filled bushing, porcelain-barrier type

View of internal parts showing deposits of disintegrated varnish compounds at the top and of litharge in the folds of the varnished cloth near the center

Power-factor tests on sections of the bushing showed that the power factor was 37.2% at the upper end above the ground shield and 1.78% at the lower end. Examination of a longitudinal section of the insulation showed that oil had migrated from the lower end, through separations in the impregnated paper, to the compound in the top. Compound dissolved in the oil had penetrated the insulation from the upper end. The paths of the oil and compound can be seen in the photograph.

Contamination of the oil has been found in oil-filled bushings of the porcelain-barrier construction. In one instance a 66-kv bushing of this type had a power factor of 26.1%. The power factor of a sample of oil was 84.9% and the dielectric strength of the oil was 14 kv. A photograph of the interior of this bushing is shown in figure 10. Examination showed deposits of disintegrated varnish compounds from the varnished cloth with which the conductor and the ends of the barriers were wrapped. Also, there were heavy deposits of litharge from the litharge and glycerine cement which was used to cement the barriers together.

Deterioration of oil and of impregnated paper under oil has been found by examination of oil-filled bushings of impregnated-paper barrier construction. Table III shows the results of examination and test of the component parts of two 66-kv bushings of this type. On No. 1 the power factors of the core and the barriers were satisfactory. Evidently deterioration of the oil gave rise to the power factor of 2.47% since the power factor was reduced to 0.49% using the same impregnated-paper parts with new oil. On No. 2 the impregnated paper of the core had a high power factor which was not reduced by drying. The insulation had become contaminated by the products of deterioration in the oil. The core was replaced.

Table III. Reconditioning of Oil-Filled Bushings

No. 1		
Power factor as received		2.47%
Power factor of parts:	**Volume, Percentage**	**Surface, Percentage**
Core	0.71	0.99
Cylinder No. 1	1.09	1.06
2	1.19	1.05
3	1.23	1.31
4	1.42	0.94
Power factor of bushing assembled and filled with new oil		0.49%
No. 2		
Power factor as received		6.80%
Power factor of parts:	**Volume, Percentage**	**Surface, Per-centage**
Core	5.52	7.48
New core	0.97	0.95
Cylinder	2.02	1.82
Power factor of bushing assembled and filled with new oil		0.71%

Volume power factor not improved by drying. Replaced.

Summary

The value of power-factor tests on bushings at higher voltages has been demonstrated. Tests at low voltages, while valuable, are inadequate. The power-factor and capacitance vs. voltage characteristics at voltages up to or above the operating voltage are important in judging the condition of the insulation.

The nature of bushing deterioration and the significance of high power factor have been shown by laboratory examinations. The findings help to establish a basis for power-factor limits, and for improvements in design and maintenance.

Excitation Circuits for Ignitron Rectifiers

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Introduction

THE development of the ignitron type of mercury arc rectifier, with its outstanding advantage in efficiency, introduced the need of a new type of excitation circuit. For the theory of how the arc is initiated, the reader is referred to the previous papers on ignitrons.[1,2]

Associated with each anode of an ignitron rectifier is an ignitor for initiating the arc. Each ignitor requires a positive impulse of current once each cycle to start the arc at the beginning of the conducting period of the main anode. In order to accomplish control of the output voltage of the rectifier, it must be possible to adjust the phase position of these impulses with respect to the supply voltage, either manually or by automatic provisions. Although the instantaneous current and power of the impulses are quite high, the impulse duration may be such that the average power is low and does not seriously affect the efficiency of rectifiers with the ratings usually encountered.

If an excitation system such as "main anode" is used with which only enough energy is applied to the ignitor each cycle to ignite the arc, the average power is very small. However, with separate excitation systems, every impulse must have the same energy and this must be adequate to ignite the arc under the most adverse conditions encountered.

The wave shape of the impulse is not critical, but the peak value of power required for reliable excitation varies considerably with the time rate of rise of current. With a high rate of rise, the voltage at which a cathode spot is formed is higher than if the voltage is applied more slowly. For a given rate of rise, this voltage varies somewhat from cycle to cycle, depending upon the exact condition of the contact of the mercury and the ignitor. This, of course, influences the time of pick-up of the main anode, so the impulses must be steep enough so that any such variations are negligible.

With the assumption that the impulses have the shape of the positive half of a sine wave, figure 1 has been plotted to show the average power of 60 impulses per second applied to a load with impulses of various peak powers and durations. The duration of the impulses is indicated by the base of the wave in terms of degrees of a 60 cycle wave. The values given by the curves must be increased by the losses in the circuit elements to obtain the total power requirements for excitation. The various systems have varying efficiencies. Circuits with which the authors have had experience have varied in their total power requirements from 75 to 300 watts per ignitor.

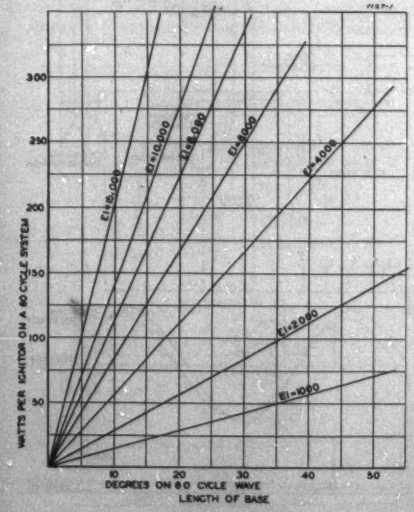

Figure 1. Average power output of a 60-cycle ignitron excitation circuit producing pulses of various durations and peak powers

There are four types of ignitron excitation circuits that have been used quite extensively in commercial applications which might be termed as follows:

(1). main anode
(2). capacitor-thyratron
(3). rotating impulse generator
(4). saturating reactor

All of the above have been applied with variations, as the art progressed, and depending upon the application. The following is a list of some of the circuits that have been worked on experimentally, but as yet have not proven sufficiently attractive to be applied commercially:

(1). peaked-wave transformers
(2). sine wave transformers phased back with thyratrons
(3). multi-anode control rectifier
(4). rotating commutator or other contact mechanism

A disadvantage of all circuits using thyratrons is that these tubes, having thermionic filaments, have limited life and constitute a replaceable item. An advantage, of course, is that voltage control is extremely flexible, simple, and efficient, since voltage control can be obtained by control of the thyratron grids. This control can consist of a bias voltage on the neutral of a sine wave grid transformer or a phase shifter in the primary of either a sine wave or a peaked wave grid transformer. A suitable phase shifter consists essentially of a wound rotor induction motor with the rotor locked in the desired phase position.

The conventional thermionic cathode of a thyratron is an average rated element; it is not suited to high over currents and thus not best suited to ignitron excitation. Ignitors require relatively high currents for short times. If only average currents were involved, ignitron excitation could be accomplished with very small and inexpensive thyratrons.

For purposes of reliable anode pick up, as well as certain control functions, it is desirable to provide a small excitation current to the main anode shield. Since this is only a nominal amount of power, it can be taken from any of the readily available sources. The figures used to

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1. For all numbered references, see list at end of paper.

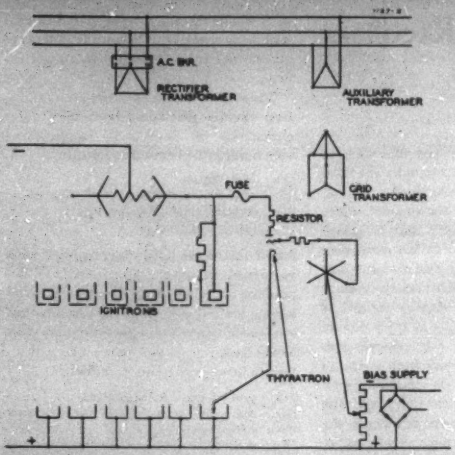


Figure 2. Diagram of a double three-phase ignitron rectifier with main anode excitation and bias control

illustrate the various excitation systems show the shield excitation accomplished in a variety of ways.

Main Anode Excitation

Figure 2 shows a schematic diagram of a simple anode fired ignitron rectifier using a grid bias method of control. A conventional double three-phase rectifier circuit is indicated for the power connections. The excitation circuit is completed for only one phase since the others are duplicates.

In this system, when an anode becomes positive with respect to its cathode, if the thyratron grid is positive, current is passed through the shunting thyratron and ignitor circuit. When this current reaches the value at which the cathode spot is formed by the ignitor, the main anode picks up and the thyratron path is short-circuited by the arc. The rate of application of voltage on the ignitor is a function of the voltage of the rectifier and the amount of grid delay used. The ignitor voltage collapses sharply when the main anode picks up. In this circuit only sufficient energy to ignite the arc is used each cycle and the average excitation power is very small. The major portion of the loss is the power required for heating the thyratron filament. Also, there is ample power available, since it comes from the rectifier transformer.

Although this system is highly efficient and most positive in action, it has certain limitations. Since the ignition voltage must come from the main transformer, arc pick-up does not take place until the anode voltage has reached ignitor voltage. This voltage is such that a 300 volt ignitron rectifier with anode firing operates at a minimum grid delay of approximately 8 degrees. Furthermore, because of the cycle to cycle variation in ignition voltage, this delay angle is not strictly uniform. This tends to cause some unbalance between main anodes, between phase groups, and between more than one rectifier on the same bus, all at low loads. At loads of one-quarter full load and higher, this effect vanishes.

In this circuit the ignition current must also pass through the load. Therefore, at loads below ignition value the entire load current passes through the thyratrons. Actually this is not very important since currents below ignition currents are well within the limits of the thyratrons used, even though maintained for the full load-conducting period.

With main anode excitation, the duty on the thyratron is probably more severe than in separate excitation circuits using thyratrons, since in the former, if an ignitor does not pick up, the current in the thyratron is limited only by the load demands, the resistance in the thyratron ignitor circuit, and the collapse of the interphase transformer voltage.

Capacitor-Thyratron Excitation

Figure 3a shows an excitation circuit in which a capacitor is charged through a resistor from a sine wave transformer. At a point near maximum positive charge the capacitor is discharged through the ignitor by triggering the thyratron. The principal voltage and current waves are shown in figure 3b. The front of the wave produced is very sharp and the tail is determined by the capacity and resistance of the circuit. The front can be sloped if desired by placing an air core reactor in the discharge circuit.

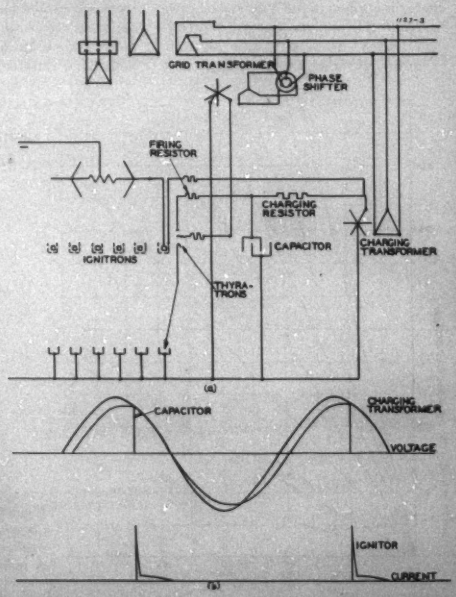


Figure 3. Ignitron rectifier circuit using capacitor - thyratron excitation with resistance charging

(a) Circuit diagram

(b) Voltage and current waves

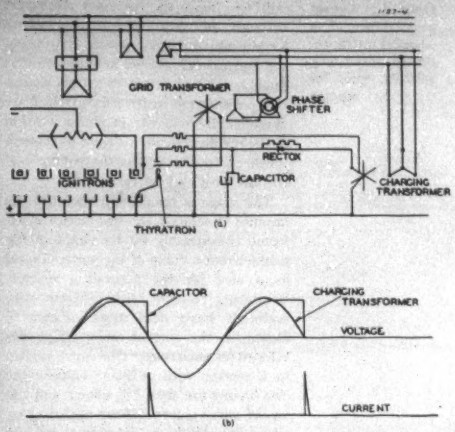


Figure 4. Ignitron rectifier circuit using capacitor - thyratron excitation with Rectox charging

(*a*) Circuit diagram
(*b*) Voltage and current waves

This circuit is simple and direct, and has the advantage of some follow-up current from the charging transformer after the pulse, which maintains an arc for 30 or more degrees and aids pick up of the main anodes at very low loads where the interphase transformer does not function. However, since the capacitor is charged through a resistor and this resistor must limit the follow current, the circuit is limited in the voltage that can be used without prohibitive loss.

The circuit permits a grid delay range of approximately 60 degrees. If a greater delay angle is desired, a transfer switch is necessary to shift connections between the charging transformer phases and the thyratrons. The power consumption can be reduced somewhat by using a reactor in place of the charging resistor. However, with a reactor the range of grid delay is considerably less and the power saved does not justify its use.

A modification of the capacitor-thyratron circuit, in which the capacitor is charged through a Rectox instead of a resistor, is shown in figure 4. This method of charging reduces the power requirements by about 50% and permits a wide range in choice of voltage with a corresponding range in impulse power. The power drawn from the line for either circuit has a power factor of nearly unity.

This circuit permits a wide range of grid delay, without switching terminals. However, if a wide range is used, it cannot be done with a grid bias, but it is necessary to use a phase shifter and a peaking transformer.

Impulse-Generator Excitation

By using concentrated fields and a suitable distribution of armature winding, a rotating synchronous generator can be built which produces impulse voltages. Such a winding arrangement, together with the waves produced and the connections to an ignitron rectifier are shown in figure 5. The impulses produced by units that have been built have a length of about 20 degrees on a 60 cycle base.

Grid delay with this type of excitation is obtained in either of two ways. In one, the generator is driven with a wound rotor induction motor, the necessary d.c. field being provided by d.c. in a pair of the windings. The phase position of the rotor is shifted by shifting the d.c. excitation from one to another of the pairs. Another method is to use a synchronous driving motor with frame shifting equipment.

The impulses provided by rotating impulse generators are highly satisfactory for ignitron excitation and the power requirements compare favorably with other types of efficient separate excitation systems. Furthermore, there are no replaceable parts except field brushes within the normal life of small synchronous M-G. sets.

The impulse generator has the disadvantage of being a rotating device somewhat bulky and noisy. For some applications a more serious objection is the synchronous motor's tendency to hunt and the reflected effect on the output voltage of the ignitron rectifier. By suitable choice of driving motor, this tendency to hunt can be kept to a value having negligible effect on the load where the rectifier capacity is small compared to the supply system. However, where

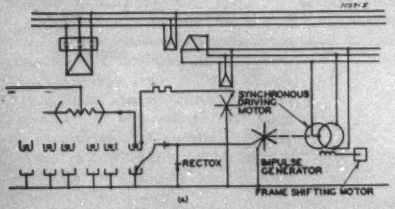
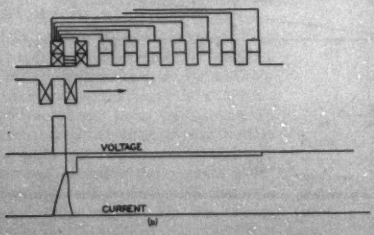
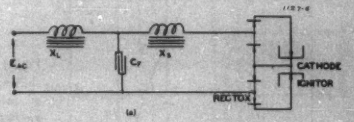


Figure 5. Ignitron rectifier circuit using a rotating impulse generator

(*a*) Circuit diagram
(*b*) Voltage and current waves





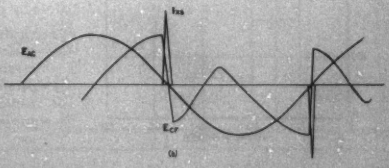


Figure 6 (right). Saturating reactor excitation circuit for ignitron rectifiers

(*a*) Circuit diagram
(*b*) Voltage and current waves

E_{AC} = supply voltage
X_L = linear reactor
C_F = firing capacitor
X_S = saturating reactor

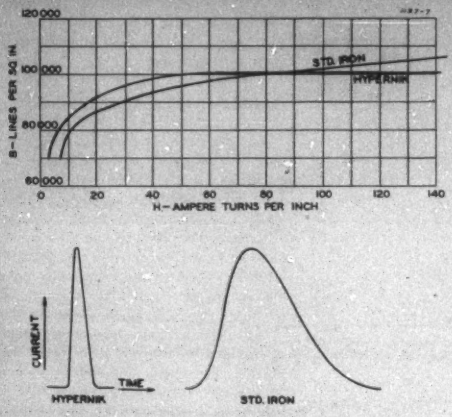


Figure 7. Current wave shapes of a saturating reactor excitation circuit with different types of reactors

the rectifier load is so large that fluctuations in the load affect the frequency of the supply system, it is possible for the natural periods of the impulse generators and the supply system to be such that violent fluctuations build up. Since the size and maintenance features of impulse generators limit their attractiveness to large installations, the danger of hunting practically precludes their use.

Saturating-Reactor Excitation

Figure 6a shows a circuit, utilizing reactors and capacitors, which will produce power impulses suitable for ignitron excitation. The linear reactor in this circuit has an iron core with an air gap and is designed to have a constant reactance for various voltages up to the rated voltage and frequency of the circuit. For a 60 cycle circuit, this reactance is approximately 30% of the reactance of the firing capacitor. The saturating reactor is built with a closed iron core and a winding such that at the rated voltage of the circuit, it will draw a large peak of magnetizing current. This peak of magnetizing current occurs when the capacitor, C_F, is charged to its peak value of voltage; hence the capacitor discharges through the saturating reactor and a large peak of current results. By using the Rectox units shown in figure 6a, it is possible for one circuit to supply excitation power to two ignitron tanks which are diametrically opposite in phase position in the rectifier circuit. Figure 6b shows a set of curves illustrating the voltage and current for a cycle of operation.

The shape of the current wave for the impulse developed by this circuit is affected considerably by the shape of the magnetization curve of the material used as a core for the saturating reactor. Saturating reactors with different core materials have been tried. Figure 7 illustrates the current wave shape developed for each case. One curve applies to a reactor with ordinary transformer iron having less than 1% silicon, and the second curve is for a reactor with Hypernik core. With a saturating reactor using a Hypernik core, it is possible to develop a peak power one hundred times the average power input. Some tests were made using this circuit with a resistor load to show the peak voltage and current it could develop for various values of constant resistance, and the results are plotted in figure 8.

In this circuit, the phase position of the impulses, which control the ignitron voltage, must be controlled by shifting the input voltage to the excitation circuit. This may be accomplished by means of a phase shifter which must shift the entire excitation power. The phase shift-

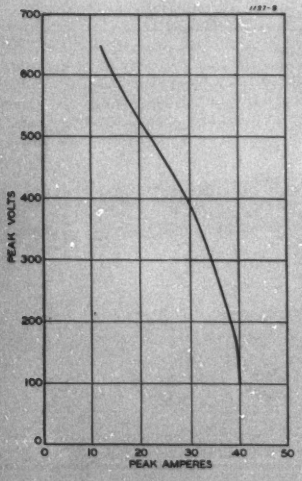


Figure 8 (left). Peak voltage and current developed by the saturating-reactor circuit using a Hypernik reactor

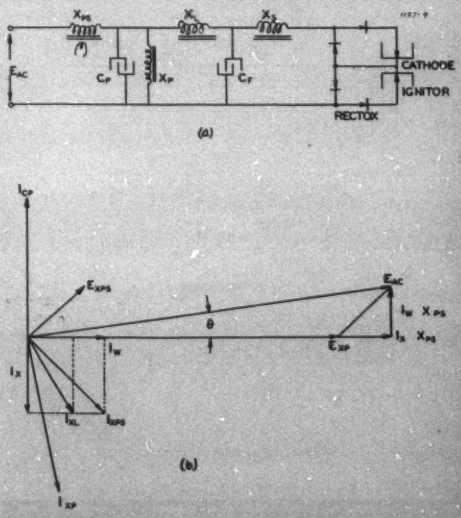


Figure 9. Phase-shifting network for a saturating-reactor excitation circuit

(a) Circuit diagram

(b) Vector diagram

E_{AC} = supply voltage

X_{PS} = phase-shifting reactor

C_P = parallel capacitor

X_P = parallel reactor

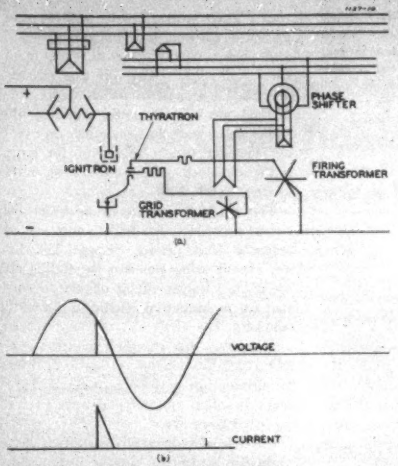


Figure 10. Ignitron rectifier circuit with sine-wave phased-back excitation

(*a*) Circuit diagram

(*b*) Voltage and current waves

ing may also be accomplished by means of a phase shifting network. Figure 9*a* shows a diagram of such a network.

The phase shifting circuit contains all the elements of the circuit shown in figure 6*a* with three additional components. The phase shifting reactor is capable of a gradual change in reactance over a 10 to 1 range by means of d.c. saturation. The parallel reactor and capacitor operate with a circulating current larger than that drawn by the excitation circuit and act as a power source for that circuit. The phase position of the voltage across the parallel combination can be adjusted by controlling the phase shifting reactor.

If the parallel reactor has a closed iron core, and is designed so that normally it operates with considerable saturation, then the voltage across X_P and C_P will remain almost constant with considerable fluctuation in line voltage or change in the reactance of the phase shifting reactor. Figure 9*b* is a vector diagram illustrating the voltage and current phase relations in this circuit.

As shown here, the loss component of current through X_{PS} determines the phase shift for a given value of reactance in X_{PS}. The reactive component of current in X_{PS} operates to maintain constant voltage across C_P and X_P. This reactive component is a balance between current taken by C_P and X_P which varies according to line voltage due to the fact that X_P is saturating. In practical operation this permits a 90° phase shift with no perceptible change in peak voltage output. The line voltage may likewise change 30% with only a 1% change in voltage across C_P and X_P.

Peaked-Wave-Transformer Excitation

The impulse produced by a conventional peaked wave transformer has the shape desired for ignitron excitation. Such a transformer, connected to block out or by-pass the negative peaks, is a satisfactory circuit. However, in a peaked wave transformer the impulse energy is stored periodically in the magnetic circuit and it is found that a transformer to produce impulses of the magnitudes required for ignitron excitation is prohibitively large.

Sine-Wave Phased-Back Excitation

Ignitors can be fired with 60 cycle sine waves. However, if the ignition is permitted to take place on the front of the wave from a circuit having capacity enough to supply the instantaneous power required by ignitors, the power loss is prohibitive. To avoid this high loss the voltage can be phased back or blocked by a thyratron, until a later point in the cycle where the follow current is much less. Such a circuit is shown in figure 10. In any event, the degree to which ignition can be phased back is limited and the minimum follow power attainable results in rather high excitation losses. Furthermore, the power consumption varies greatly with the angle of phase back so the range of grid control is very limited and the highest loss is at the minimum delay angle where rectifiers operate the majority of the time. Practically, control of rectifier voltage with this type of excitation requires that a phase shifter be placed in the power supply to the excitation circuit.

A modification of the circuit shown in figure 10 can be made by placing a single resistor in the neutral of the excitation transformer instead of the individual resistors in the ignitor leads. Such a resistor would cause the circuit to produce 60 degree pulses as in a six phase rectifier.

Multianode-Control Rectifier

The sine wave-phased back circuit can be modified as shown in figure 11, so so as to permit the use of a miniature multianode grid controlled rectifier. Since such a rectifier has a common cathode,

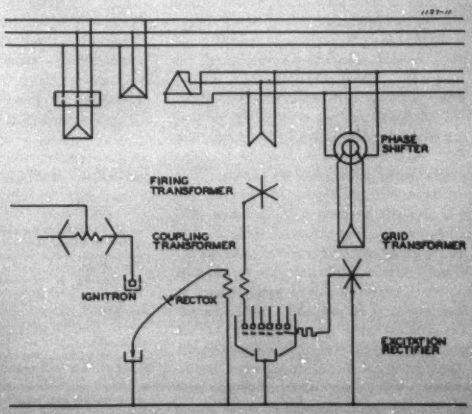


Figure 11. Ignitron rectifier circuit with miniature grid-controlled rectifier excitation

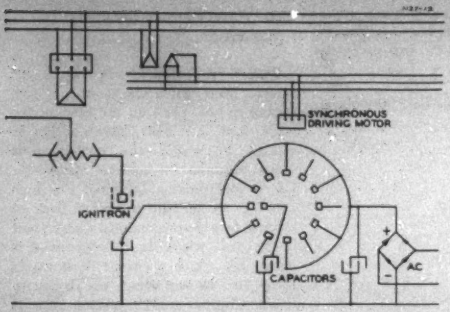


Figure 12. Rotating-commutator excitation system for ignitron rectifiers

coupling transformers are required in order to segregate the individual ignitor circuits.

The advantage of this circuit is that it retains low energy electronic control comparable to thyratron control, but eliminates the replaceable tubes. Its attractiveness is limited to pumped ignitrons where the addition of a small auxiliary pumped device involves little disadvantage. The range of grid control available with this circuit is limited, unless the entire excitation power is shifted, since, in common with the phased-back circuit, the excitation power varies widely with the phase back angle.

Rotating-Commutator Excitation

Figure 12 shows a system of excitation in which a rotating contact member is driven by a synchronous motor. As the moving contact passes under the brushes connected to the d.c. source, the capacitor is charged and when it passes under the brushes connected to the ignitors, the capacitor is discharged through the ignitor. Obviously, the capacitor could be connected to the stationary member and the ignitor contacts rotated if dictated by convenience. Control of voltage can be obtained either by means of rotating the stationary contact members or by any convenient means of shifting the phase position of the driving motor.

This system is most efficient and flexible as regards circuit constants, but it has the disadvantage of including a rotating member and sliding contacts with the resulting maintenance requirements.

Conclusions

In general, the development of the ignitron has progressed to a point where several circuits are available for excitation. These will provide positive and accurate ignition independent of load, and their attractiveness depends upon the application. Any of the circuits described in this paper which are in commercial use have a power consumption sufficiently small that the effect on overall efficiency is less than .1% for large units, and does not exceed .4% on units as small as 200 K.W.

The use of thyratrons in an excitation circuit provides a flexibility and speed of response that cannot be matched by any circuit using elements depending on mechanical movement or change of current in an inductive circuit, to provide control.

The saturating reactor excitation system, consisting entirely of static devices, by elimination of tube replacement appears to offer practical advantages for many applications.

When used with a phase shifting network, the saturating reactor system can be controlled with small power devices or compensating circuits, and has a speed of response adequate for most applications.

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A Simple Method for Determination of Ratio Error and Phase Angle in Current Transformers

Correlation of Significant Constants of Current Transformers

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ASSOCIATE AIEE

Synopsis: Up to the present time current transformer performance has been described by curves which show ratio error and phase angle over a range of current at various values of burden, (ohms) power factor, and frequency. The number of curves that are required to cover all possible conditions is so great as to render them, by their very bulk, practically useless. Another limitation is that they do not describe performance under transient conditions.

Performance of other types of transformers and certain other apparatus is invariably calculated from a few easily measured constants, according to simple standard formulas. Up to the present time, available methods for calculation of current transformer performance have had the disadvantage of either being difficult to use, or of depending on constants difficult to measure, or else they have not been sufficiently accurate for general use.

A method is described which depends on the following constants:

1. Open-circuit saturation curve measured in the usual way.
2. Secondary coil resistance.
3. Equivalent leakage reactance calculated from the voltage of an exploring coil enclosing the maximum value of leakage flux.

The method includes several important short cuts in the calculation which reduce the numerical work to a practical minimum. Curves are plotted which allow direct reading of the exact components of exciting current which cause ratio error and phase angle.

The objects of the paper are:

1. To present a practical method of calculation.
2. To establish constants (1), (2), and (3) as the fundamental quantities which determine real excellence of the transformer.

I. The Need for a Simple Method for Description of Current-Transformer Performance

THE conventional ratio and phase-angle curves for a current transformer are often inadequate for solution of a particular problem. Furthermore, the tests from which such curves are plotted are expensive, and the data are not available for many of the older transformers now in service.

A simple method for determining current transformer performance from a few easily measured constants (as power transformer performance is determined from copper and iron loss and impedance measurements) has been earnestly sought. This paper will present a method which the author believes to be the best so far proposed.

II. Theory of Current Transformation

The general principle of calculation of current transformer performance is very simple. The ampere turns in the secondary coil are less than those in the primary coil only because of the ampere turns lost in circulating flux in the core. Hence, we need only to calculate the ampere turns or magnetomotive force drop around the magnetic circuit.

However, on account of the leakage flux in the core, this is not as simple as it sounds. This leakage flux is principally the flux which passes between primary and secondary windings, and completes its path in the core outside the primary winding (figure 1). The current transformer is different from other transformers in that this leakage flux is relatively large, often larger than the working flux. This flux has been investigated experimentally[1] and theoretically,[2,3] but no method has been developed by which it can be exactly calculated. Furthermore, it is well known that it enters the core, not at one point, but all over the whole surface, so that it is not the same at any two points in the core

If any one of a number of approximate methods is used to calculate the leakage flux, the ampere turns to circulate it through the core can be calculated by dividing the core into a number of parts, assuming a constant equivalent flux in each part. This is the basis of the method described by Mr. Sinks,[2] and this method, although still not absolutely correct (its limitations are fully described by Mr. Sinks), is the most nearly correct method now available. Its real limitation is the great amount of numerical work involved.

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1. For all numbered references, see list at end of paper.

III. Assumptions Which Simplify Calculation

Certain methods have been developed for simplifying this calculation. The most simple method, which does very well for ring type transformers, is to neglect the leakage flux altogether.[4] Another method assumes an experimentally determined flux, approximately related to an average value of leakage flux, to flow in the whole core.[5] These methods are not suitable for general use, because they do not use the real magnitude and distribution of the leakage flux.

IV. Combination of Best Features of All Methods

Giving first consideration to the fundamental soundness of the method, we can say that the method should—

1. Consider division of the core into several parts, as discussed in II with different leakage fluxes in the different parts.
2. Base the distribution of the leakage flux and the division of the core, on values of leakage flux actually existing in the core as measured by exploring coils (figure 2). The exploring coil can be simply ten turns of fine wire.

Giving second consideration to the aspects of economics and convenience, we can say that the method should not divide the core into more parts than is necessary for the required accuracy. Here a good deal of experience is required. Any particular division of the core into any finite number of parts is an empirical device, and can be justified only by general experience which shows that it works. The final result cannot be shown, in any rigorous way, to be the best possible result.

It will help to remember the primary objects of the investigation, and to make the division of the core accordingly. The first object is to calculate an error that is at least as large as the real error, to be on the safe side. The second is to get consistent results, to be able to compare transformers on a true basis. The first object can be obtained if the average flux values in each part of the core are taken to be sufficiently large, even if the

core is not too well divided. The second object will be obtained if the flux measurements are made in the same way on all transformers of the same type.

Of course, we do not want to calculate an error too much larger than the true value. This is the disadvantage of not dividing the core at all, but considering the measured value of leakage flux to flow in the whole core; the calculated error will always be too large.

Division of the core into two parts, with the real leakage flux measured by exploring coils, is a compromise which the test results to be cited, and other tests, show to be suitable for general use with dry type transformers. This compromise is, however, definitely not fundamental; the general method to be described can be used with any desired division of core.

When the ratio error exceeds five per cent, the iron is usually working near saturation, and much of the leakage flux which is in the iron at normal flux densities leaves the core at the higher density and completes its path in the air leaving less flux in the core than would be expected. The result is that this method of calculation will give errors which are considerably too large when the error exceeds five per cent. As the method is conservative, it is still useful.

Actually less than the value of flux as measured by the exploring coil shown in figure 2 exists in practically all of the core. It is obviously conservative to assume that it exists in the half of the core which is outside the primary coil. Mr. Sinks has shown that the leakage flux at the center of the core inside the secondary is effectively reversed to the leakage flux in part of the core just outside the secondary. A reasonable assumption, confirmed by tests, is that the average effective value of leakage flux in the inside half of the core is zero, and that the only flux to be considered is the working flux.

V. Simplification of Numerical Work

The proposed method of determining the leakage flux and its distribution does not solve a real difficulty attending the problem—the amount of numerical work for a solution.

Several short cuts have been worked out which do not detract from the accuracy of the calculation. These are:

1. Substitution of equivalent reactance for the leakage flux. It can be shown (appendix I) that the transformer with magnetic circuit divided into two parts, one with, one without, leakage flux, can be represented by the equivalent circuit of figure 4, where the reactance X_L corresponds to the leakage flux and can be determined from the exploring coil voltage at normal current by—(see appendix II)

$$X_L = \sqrt{\left(\frac{N_s}{N_x}\frac{E_x}{I_s}\right)^2 - R_s^2}$$

I_s = secondary current
R_s = secondary coil resistance
N_s, N_x = number of turns in the secondary and exploring coils, respectively
E_x = induced voltage in the exploring coil

(2). When the transformer is considered as the equivalent circuit in figure 4, the problem of calculating primary (input) current from the secondary (output) current is simply vector algebra. The fact that we have limited the method to five per cent ratio error (approximately five per cent total exciting current maximum) justifies the assumption that the voltage drop in X_L is not $(I_s - I_{s1})X_L$ (see figure 4) but I_sX_L, and the voltage on the number 2 exciting branch is $I_s(Z_b + R_s + X_L)$ (adding vectorially). The calculation of performance is then exactly as if the two exciting branches were two separate current transformers, one with burden $Z_b + R_s$, the other with burden $Z_b + R_s + X_L$, and the ratio and phase-angle errors will be the sum of the errors of the two.

3. It is well known[7] that the component of exciting current which produces ratio error is:

$F \cos\theta + M \sin\theta$

F, M = watt reactive components of exciting current, respectively

$\cos\theta$ = burden power factor

This value, added to the secondary current, gives the primary current reversed. The formula is:

$$\text{per cent ratio: per cent turns ratio} + \frac{100\,(F\cos\theta + M\sin\theta)}{I_s}$$

I_s = secondary current

Calculating the value of $F \cos\theta + M \sin\theta$ from the ordinary open-circuit secondary saturation and power factor curves is not difficult, but calculation of a number of points is tedious. Now the ordinary saturation curve is plotted between exciting current, which is $\sqrt{F^2+M^2}$, and secondary voltage. It is not much more difficult to plot $F \cos\theta + M \sin\theta$ for a number of values of $\cos\theta$, instead of $\sqrt{F^2+M^2}$, and the desired value can then be read directly.

$$\text{Phase angle} = \frac{3438}{I_s}(M\cos\theta - F\sin\theta)$$

The phase-angle component is $M\cos\theta - F\sin\theta$, and a similar set of curves can be plotted for this value.

Figure 5 is an example of such a set of curves for one transformer and figure 7 is a set of $F\cos\theta + M\sin\theta$ curves for a different transformer. The log-log co-ordinates of figure 5 are more useful if the lower range of the curves is important. This idea was originated by A. M. Wiggins.[6]

The data needed for calculating performance then are:

(1). Saturation curves of the form $F\cos\theta + M\sin\theta$ and $M\cos\theta - F\sin\theta$ plotted against secondary voltage, for a number of values of $\cos\theta$ (see figure 5).

(2). Secondary winding resistance.

(3). Leakage reactance X_L measured according to appendix II.

The procedure is:

(1). Given burden and power factor, determine the total burden on the right hand exciting branch of figure 4. (Burden + secondary resistance = Z_1.) Also determine the sum of this burden + X_L, which is the burden on the left hand exciting branch. $Z_1 + X_L = Z_2$. (Vectorial addition.)

(2). From these two values of burden in ohms and the secondary current, calculate the voltages on the two exciting impedances.

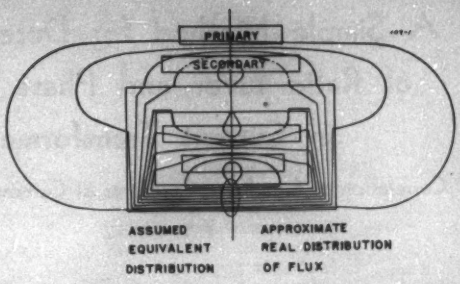
$E_1 = I_sZ_1$
$E_2 = I_sZ_2$

(3). From the $F\cos\theta + M\sin\theta$ curves, read values for E_1 and E_2 and find per cent ratio by—

$$\text{per cent ratio} = \text{per cent turns ratio} + \frac{100}{2}\times\left[\frac{(F\cos\theta + M\sin\theta)_1}{I_s} + \frac{(F\cos\theta + M\sin\theta)_2}{I_s}\right]$$

Figure 1. The leakage flux passing in the space through and between coils completes its path through the core

The leakage flux is relatively large in a current transformer



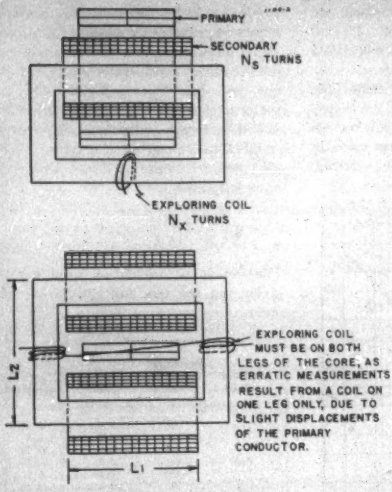

PRIMARY
SECONDARY
N_S TURNS
EXPLORING COIL
N_X TURNS
EXPLORING COIL MUST BE ON BOTH LEGS OF THE CORE, AS ERRATIC MEASUREMENTS RESULT FROM A COIL ON ONE LEG ONLY, DUE TO SLIGHT DISPLACEMENTS OF THE PRIMARY CONDUCTOR.
L2
L1

Figure 2. The most direct and simple as well as the most nearly correct method for determination of leakage flux is measurement by exploring coils

The lengths L1 and L2 represent relative (not absolute) lengths of the part of the magnetic circuit which can be considered to carry no leakage flux and all the leakage flux, respectively, in a through-type transformer

The subscripts 1, 2, refer to the two parts of the core; the division by 2 takes account of the fact that each component is for only half of the core, whereas the saturation curves are for the whole core. It will be noted that the exact turns ratio must be known. This ratio is often difficult to measure, but the manufacturer can always supply it. It may also be difficult to place the exploring coil on a transformer. This also is easy for the manufacturer, however. General use of this method will probably depend on the manufacturer's measurements of exact turn ratio and leakage flux.

$$\text{Phase-angle minutes} = \frac{3{,}438}{2} \times \left[\frac{(M \sin\theta - F\cos\theta)_1}{I_s} + \frac{(M\cos\theta - F\sin\theta)_1}{I_s}\right]$$

VI. Comparison of Tests and Calculations

The constants which determine the performance of the transformer at a given frequency are:

(1). The secondary coil resistance.

(2). The secondary leakage reactance X_L measured according to appendix II.

(3). The $F\cos\theta + M\sin\theta$ and $M\cos\theta - F\sin\theta$ curves for exciting current plotted against secondary voltage.

(4). The burden.

(5). The secondary current.

The fact that this method gives correct results for ring type transformers, in which there is no leakage flux, has been amply demonstrated.

The method has been demonstrated on several wound type transformers, and the constants for one wound type and one through type transformer will be given, together with calculated and measured results.

(a) Wound-Type Transformer

Secondary coil resistance:

0.3 ohm. (R_s)

Secondary leakage reactance:

Exploring coil voltage E_x 0.148 in 10 turns ($N_x = 10$)
At I_s = secondary current = 5 amperes
N_s = secondary coil turns = 239
From equation 7, appendix I

$$X = \sqrt{\left(\frac{0.148 \times 239^2}{5 \times 10}\right) - 0.31^2} = 0.638 \text{ ohm}$$

The $F\cos\theta + M\sin\theta$ and $M\cos\theta - F\sin\theta$ curves are given in figure 5.

The calculation of a given point is as follows:

Secondary current = 5 amperes	
Burden = 0.6 ohm, 90 per cent power factor =	$0.54 + j\,0.262$
Add R_s (secondary coil = ($Z_1 = 0.89$ ohm, 96 per cent power factor) Z_1 =	0.31 $0.85 + j\,0.262$
Burden voltage $E_1 = 4.45$	
Add X_L =	$j\,0.638$
$Z_2 = 1.24$ ohms 69 per cent power factor	$0.85\ \ j\,0.9$
Burden voltage $E_2 = 6.2$	
From figure 5, at $E_1 = 4.45$, $(F\cos\theta + M\sin\theta)_1$ =	0.0133
at $E_2 = 6.2$, $(F\cos\theta + M\sin\theta)_2$ =	0.0229
Per cent ratio = $\left\{\frac{100}{2}\right.$ per cent turns ratio $\left.\frac{(0.0133+0.0229)}{5}\right\}$ =	$99.584 + \frac{0.362}{99.946}$
Test value =	99.80

The curves of figure 6 were calculated in the same way, and one who desires to may check them very rapidly by the use of tabular calculations.

(b) Through-Type (Two-Coil) Transformer

Good results are generally obtained by dividing the core into two equal parts, in the case of a wound type current transformer, but the division should not be made quite this arbitrarily for a through type current transformer. If the length of magnetic circuit not enclosed by the coils is taken as the part carrying leakage flux, and the axial length of the coil is taken as the part not carrying leakage flux, better results are generally obtained. These two lengths are, more often than not, nearly equal, so that the final division is usually not far from division into two equal parts, but some designs are made with unusually long yokes which carry the leakage flux, and account should be taken of their length. The lengths of these parts of the circuit are usually easily measured, according to figure 2.

The particular design in question was such that the core could be considered to be divided into equal parts.

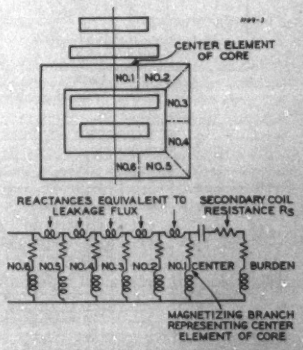


Figure 3. The flux at the center of the core inside the secondary coil is actually less than enough to generate the total burden voltage, because the "leakage" flux passing through the body of the secondary coil actually links some of the secondary turns and induces a part of the secondary voltage

This real reduction of flux in the center element of core can be represented exactly by a negative series reactance or a capacitor C

Each successive element of the core, starting from the center element, carries a greater part of the real leakage flux, represented by added series reactances, and the network is an accurate equivalent

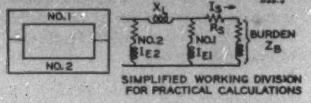


Figure 4. A practical working equivalent for figure 3 is the two-branched network

The curves for this transformer are given in figure 7.

The secondary resistance was 0.345 ohm. (R_s)

The secondary turns (N_s) were 280; ratio 1,400/5 amperes.

Two exploring coils were used, one on each yoke of the core, ten turns each, in series as in figure 2 (N_x=20). Erratic results would be obtained from measurements on only one exploring coil, as only slight displacement of the primary conductor causes considerable shifts in leakage flux, which has negligible effect on performance, but which causes considerable difference in individual coil voltages.

The total voltage of two exploring coils (E_x) was 2.15 volts at I_s=15 secondary amperes, and thus

$$X_L=\sqrt{\left(\frac{280}{20}\frac{2.15}{15}\right)^2-0.345^2}=1.98=2.0 \text{ ohms}$$

The details of calculation need not be given, but the test and calculated data are—

Burden Ohms	Secondary Current Amperes	Per Cent Ratio Error Test	Calculated
1.0	50	0.5	0.59
	75	3.0	4.5
2.0	25	0.1	0.28
	50	3.3	3.1
	55	4.2	4.7
4.0	25	0.7	0.75
	35	5.5	5.4

At larger currents, where errors are much larger, the test values do not agree with calculation.

This design is typical of two-coil through type transformers, and the two-ohm equivalent internal reactance is also typical for this ratio. The burden may often be less than the equivalent internal impedance, so that the performance of the transformer may sometimes not be much affected by burden.

If the ratio is higher than 1,400/5 the internal impedance will be higher, increasing approximately as the square of the ratio, and if the core section is increased the internal impedance will increase almost in proportion. The result is that a two-coil through type current transformer of conventional design will not perform well at primary currents much above 25,000 primary amperes, regardless of the amount of iron in the core.

VII. Other Uses for Saturation Curves and Secondary-Coil Resistance Data

(1) Transient Performance

The use of the secondary coil resistance and saturation curve for determining per-

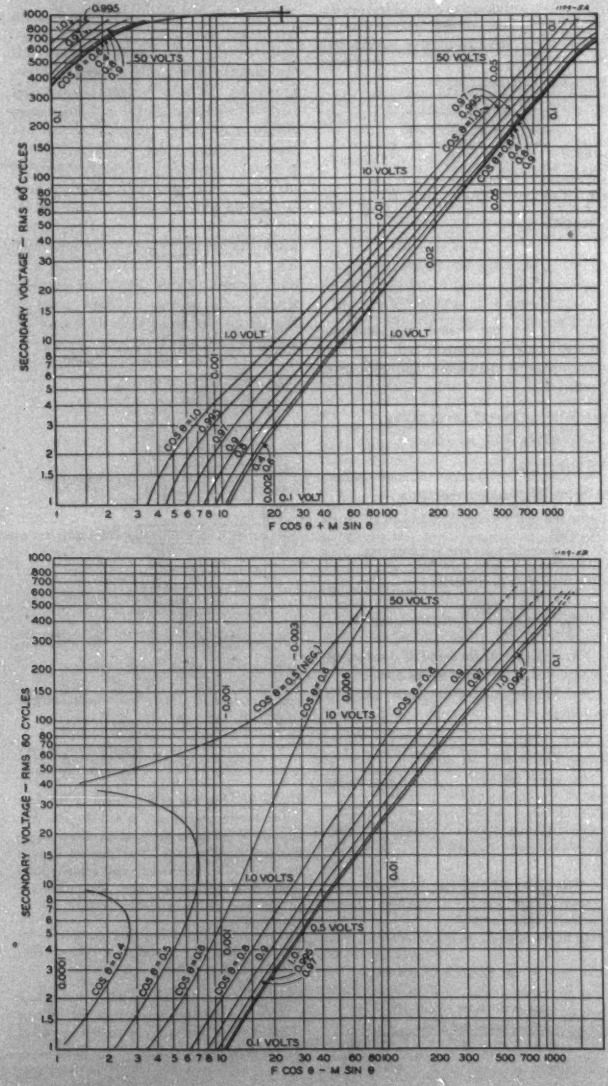


Figure 5. F cos θ + M sin θ and M cos θ – F sin θ curves for a typical transformer

These are calculated from the watt (F) and reactance (M) components of the open-circuit secondary saturation curve. Cos θ is the burden power factor

formance at transient currents has been fully described in previous papers.[1,3]

(2) Parallel Connection

When current transformers are connected in parallel, the primary current of one of the transformers may be very low, or even zero. If it is very low, while the burden voltage is relatively high because of current supplied by the other transformers in parallel, the effective burden impedance (:volts/current) is very high, higher than any usual burden, and the performance of the current transformer at such a burden will seldom be given by the standard performance curves. The performance can then easily be determined by the method given.

If the primary current is zero (primary circuit open) the exciting current drawn by the dead current transformer can be read from the same saturation curve, and its effect on the current supplied to the burden calculated in the same direct way.

VIII. Constants Determining the Excellence of a Current Transformer

The real excellence of a current transformer is determined by examination of ratio and phase-angle data. However, it is not economical, as has been pointed out, to measure ratio and phase angle at every possible condition, and comparison of overcurrent data on two current transformers is usually awkward, and often inconclusive.

When current transformers operate relays, ratio errors of less than five per cent are usually of no consequence. The power factor of the total burden with the usual relays will be in the neighborhood of 60 per cent. If the primary current is the common figure of 10 times normal, or 50 amperes secondary current, $F \cos \theta + M \sin \theta$ must be 2.5 to produce an error of 5 per cent. Then the magnitude of the voltage, according to the $F \cos \theta + M \sin \theta$ curves, at which $F \cos \theta + M \sin \theta$ will be 2.5 is one general measure of the excellence of the current transformer (see figure 5).

The resistance of the secondary winding and the equivalent value of X_L determine how much must be added to the connected burden to determine how much burden the transformer has to carry. Hence these figures also are measures of the excellence of the current transformer.

Thus two indices of excellence which can be readily compared are:

(1). Secondary voltage at which $F \cos \theta + M \sin \theta$ for 60 per cent power factor is 2.5.

(2). Internal resistance and reactance.

IX. Conclusions

A simple method for calculation of current transformer performance has been developed. It is not new in fundamental principles, but it is an improvement and simplification of the most accurate existing method.[3]

It is more direct in its use of leakage flux; it uses a real measured value in its calculations; furthermore, the measurement of flux is easily done with exploring coils without other special equipment. The exploring coil can be threaded through the space between core and coil in many transformers, especially older models.

The method is flexible. If further experience shows the necessity for further division of the core, two sets of exploring coils can be used with a division of the core into three parts. It can be made to be as accurate as desired.

It proposes a simple equivalent circuit for calculations which includes an internal reactance. This simplifies the calculation, and isolates and defines a constant of the transformer: the equivalent internal reactance of a current transformer is that reactance which as burden would require an additional flux equal to the maximum measurable value of leakage flux in the core. A formula for the reactance in turns of exploring coil measurements is included.

The errors in the method are on the conservative side. The real exciting current is less than the calculated value, and at the higher values, corresponding to saturation of the core, where the ratio error usually exceeds five per cent, the calculated ratio error is usually much too high. Thus, the method is useful even where it is not too accurate.

Curves are proposed for simplification of the vector algebra. This expedient is of great value when many calculations are to be made. However, this part of the method is not essential. Any correct method of vectorially adding exciting current to secondary current can be used.

The performance under transient conditions, at unusual burdens or currents (including performance of parallel transformers) can all be determined from the characteristics listed above, using available methods[2,4] for transient performance, and the method described above for performance at unusual burdens or currents.

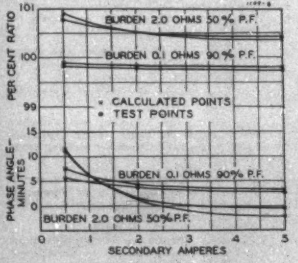


Figure 6. Calculation versus test

Wound-type current transformer calculated from figure 5, and secondary resistance = 0.31, leakage reactance 0.638

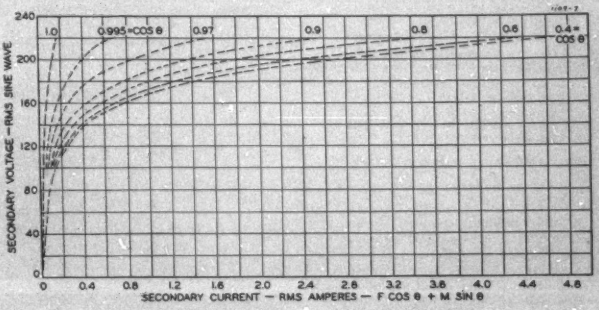


Figure 7. F cos θ+M sin θ curve for a through-type current transformer

$F \cos \theta + M \sin \theta$ is the component of exciting current which must be added to the secondary output current to get primary input current reversed (1/1 ratio basis). Example: burden four ohms at 80 per cent power factor, secondary current 50 amperes, exciting current (from curve) at 4×50 = 200 volts = 1.8 amperes. Primary current reversed = 51.8, ratio = 100 (51.8/50) = 103.6 per cent

The performance of a current transformer is shown to depend on a few simple constants of the transformer:

(1). Internal resistance

(2). Internal reactance as defined

(3). Open-circuit saturation curve

Comparison of (1), (2), and one point on curve (3) allows formation of judgment about the relative excellence of transformers.

Appendix I. Equivalent Circuit for Current Transformers

An inductance burden on a current transformer requires a voltage 90 degrees ahead of the current, and as the flux to induce the voltage is, in turn, 90 degrees from the voltage, the flux is in phase with the primary current. So we may say:

1. The flux required by an inductive burden is in phase with the primary current.

Furthermore, it is well known that—

2. The leakage flux is also in phase with the primary current.

We can combine statements (1) and (2) and say—the flux required by an inductive burden has the same phase position as the leakage flux.

As both fluxes are directly proportional to the current, they are equivalent fluxes, and the leakage flux can be represented, if desired, by an equivalent inductance in the burden.

As shown by Mr. Sinks,[8] the leakage flux at the center of the core inside the secondary coil has, in effect, a negative value, but has higher values in each succeeding element of the core. For purposes of analysis, we can separate the core elements and represent each one by an equivalent exciting branch. The fact that each element carries a certain leakage flux can be represented by an equivalent inductance in series with the current circuit, as in figure 3. The fact that the leakage flux at the center corresponds to a negative inductive reactance is represented by a capacitance in series with the first branch.

For practical work in which the core is divided into only two parts, one of which is assumed to carry no leakage flux, the circuit takes the simpler form shown in figure 4, in which the series equivalent inductance is determined according to appendix II.

Appendix II. Exploring Coil for Flux Determination

If the secondary winding of a current transformer is short-circuited, the total real linkages of flux with the secondary coil are just enough to circulate the current against the resistance of the winding. This flux can be calculated as an equivalent flux ϕ_s which links all the secondary turns.

$$\phi_s = \frac{I_s R_s 10^8}{4.44 f N_s} \tag{1}$$

I_s, R_s, N_s = secondary current, coil resistance, and turns, respectively.

This amount of flux may be considered as a working flux flowing all around the core.

If an exploring coil is placed on the outer part of the core at a point where leakage flux exists, it will develop a voltage corresponding to ϕ_s plus (vectorially) the leakage flux ϕ_L.

The exploring coil voltage will be—

$$E_x = 4.44(\phi_s + j\phi_L) f N_x 10^{-8} \tag{2}$$

j expresses the fact that the vector ϕ_L is at right angles to the vector ϕ_s. In absolute values,

$$\left(\frac{E_x 10^8}{4.44 f N_x}\right)^2 = \sqrt{\phi_s^2 + \phi_L^2} \tag{3}$$

$$\phi_L = \sqrt{\left(\frac{E_x 10^8}{4.44 f N_x}\right)^2 - \phi_s^2} \tag{4}$$

$$\phi_L = \sqrt{\left(\frac{E}{N_x}\right)^2 - \left(\frac{I_s R_s}{N_s}\right)^2} \frac{10^8}{4.44 f} \tag{5}$$

The leakage flux ϕ_L can be expressed as an equivalent reactance referred to the secondary winding of N_s turns and peak current $\sqrt{2}\, I_s$

$$X_L = \frac{2\pi f N_s \phi_L 10^{-8}}{\sqrt{2} I_s} = \frac{2\pi f}{\sqrt{2}} \frac{10^8}{4.44 f} \sqrt{\left(\frac{N_s}{N_x}\frac{E_x}{I_s}\right)^2 - R_s^2}\, 10^{-8} \tag{6}$$

$$X_L = \sqrt{\left(\frac{N_s}{N_x}\frac{E_x}{I_s}\right)^2 - R_s^2} \tag{7}$$

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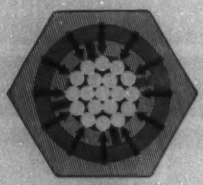

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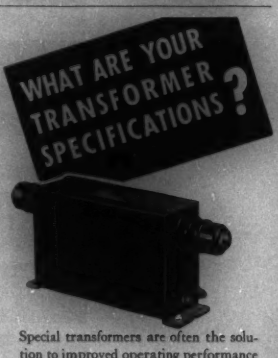

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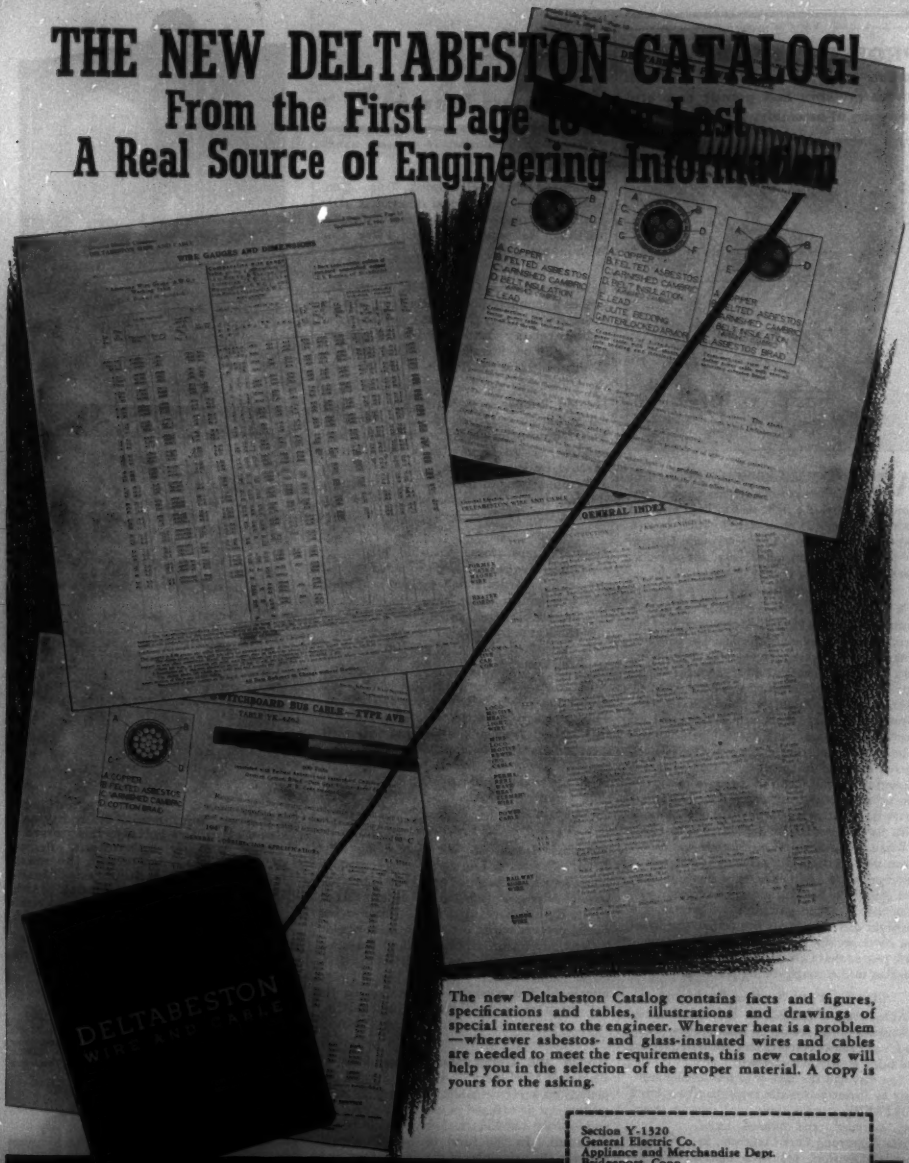

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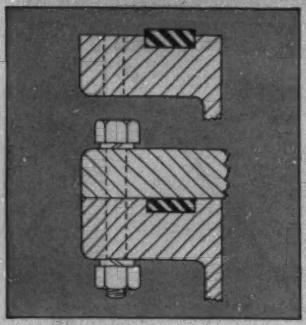

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(Free to readers, upon request to companies named)

Vulcanized Fibre.—Handbook, 40 pp. Contains technical and general descriptive data covering the properties and uses of laminated plastics. National Vulcanized Fibre Co., Wilmington, Del.

Ballasts.—Bulletin GEA-3293C, 16 pp. Describes a complete line of ballasts for Mazda fluorescent lamps. Contains comprehensive technical data; outlines, wiring diagrams, and notes on installation and operation. General Electric Co., Schenectady, N. Y.

Molded Rubber.—"A Hard Rubber Manual", 32 pp. Describes characteristics, manufacturing procedure, compounding and molding, design factors, cost variations as affected by specifications; includes charts and comparisons of rubber's physical qualities and those of other plastics. Jos. Stokes Rubber Co., Trenton, N. J.

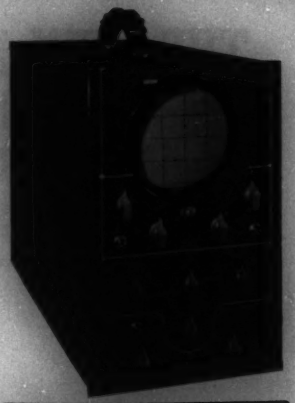
Magnetic Separators.—Catalog, 16 pp. A comprehensive reference publication on the subject of magnetic pulleys and magnetic pulley separator units, containing descriptive matter, illustrations, specifications, applications and voluminous data on the subject. The Stearns Magnetic Mfg. Co., Milwaukee, Wis.

Aluminum Data.—Reference Bulletin 1, 4 pp. The first of a series of service bulletins; lists 100 references on aluminum of special interest to manufacturers of defense materials. Many of the published articles listed are available in reprint form. Aluminum Company of America, Gulf Building, Pittsburgh, Pa.

Asbestos Insulated Wire.—Catalog 59-104B. Illustrates and describes a complete line of asbestos-insulated and glass-insulated power cables, switchboard and appliance wires, fixture wires and cords, locomotive cords, magnet wires, etc. Contains specifications, diagrams, drawings, and includes much technical data on materials used in cable manufacture. Double indexed; a plastic binding permits the catalog to lie flat when opened. General Electric Co., App. and Mdse. Dpt., Bridgeport, Conn.

Motors and Generators.—"Catechism of Electrical Machinery", 48 pp. Simple explanations are presented of electricity and magnetism as utilized in electric generators and motors, and electrical measurements are discussed. In the form of questions and answers the principles of d-c generators and motors are outlined, followed by an examination of alternators and a-c motors. Illustrations and simplified diagrams, as well as photographs and useful tables of practical applications are included. Fairbanks, Morse & Co., 600 So. Michigan Ave., Chicago, Ill.

(*Continued on page 20*)



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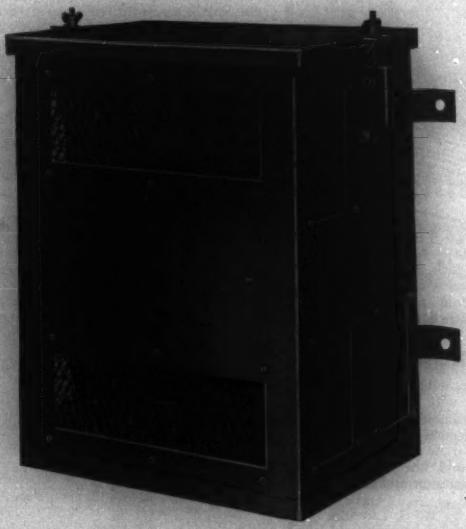

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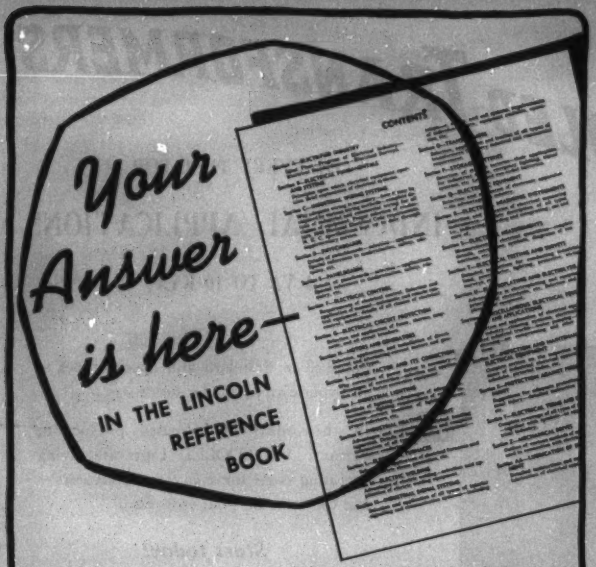

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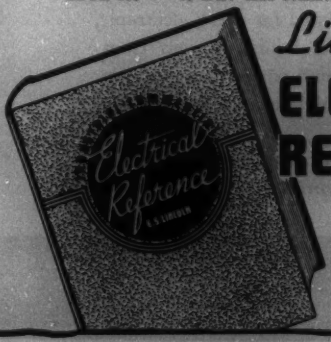

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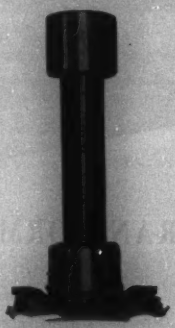
Trade Literature

(Continued from p. 18)

Dynamometers.—Catalog 30, 20 pp. Describes various types of dynamometers, test equipment and special scales. The catalog covers many types of apparatus from traction dynamometers with capacities as high as 300,000 pounds to testing machines for measuring tension of electric motor brushes. John Chatillon & Sons, 85 Cliff St., New York City.

Plastics.—Bulletin PI-10, 64 pp. Describes the manufacture of Textolite plastics, covering each step from raw materials to finished product, and indicating the variety of applications for which different types of Textolite are suited. Sections dealing with development, designing and engineering, mold making, molding, laminating and fabricated parts, industrial design, and commercial policy are included. General Electric Co., Plastics Dept., Pittsfield, Mass.

Commercial Transmitting Capacitors.—Catalog. New types, revised listings, and additional application data are covered in the second edition of this transmitting capacitor catalog. The loose-leaf book, available to those engaged in designing, building and maintenance of commercial radio and electronic equipment, is kept up to date by the new pages issued from time to time, each copy being numbered and registered in the name of the holder for just such purpose. Aerovox Corporation, New Bedford, Mass.



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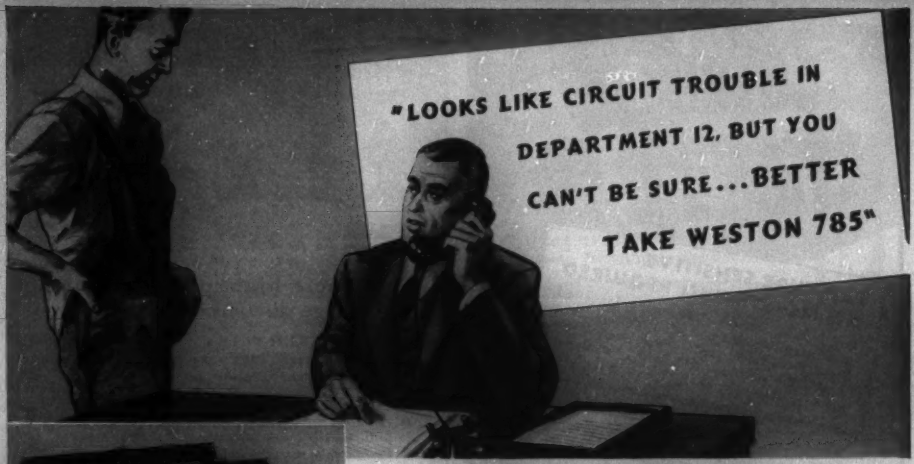

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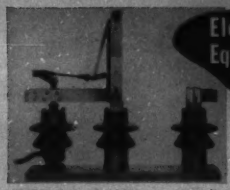

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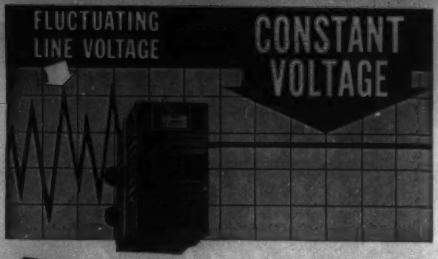

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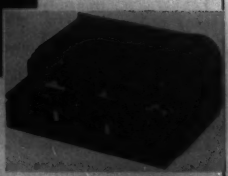

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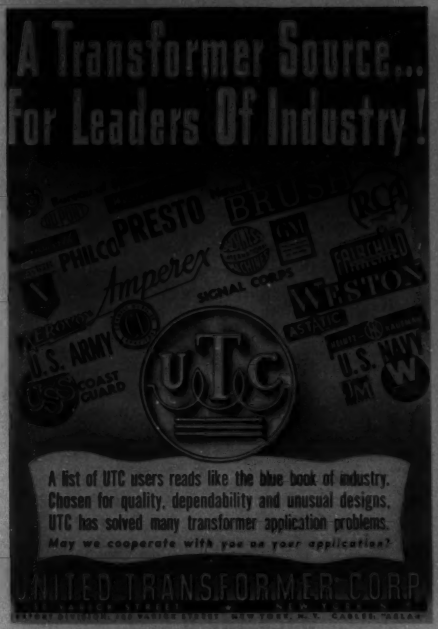

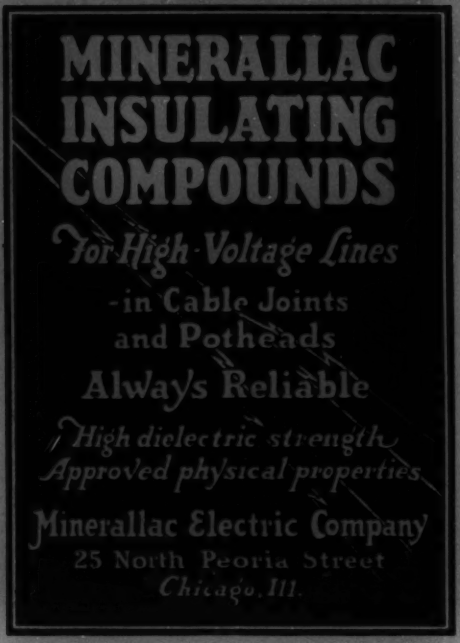

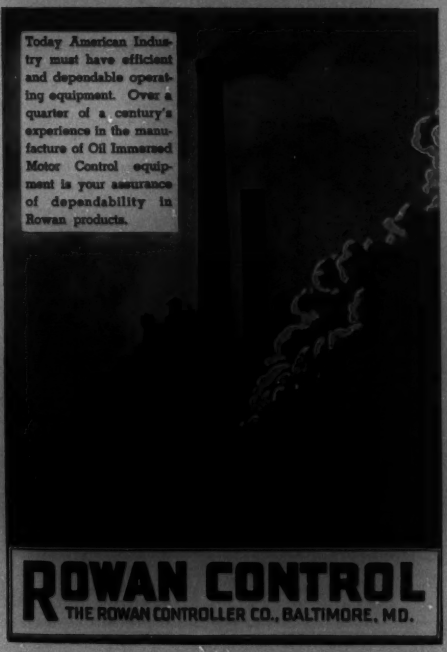
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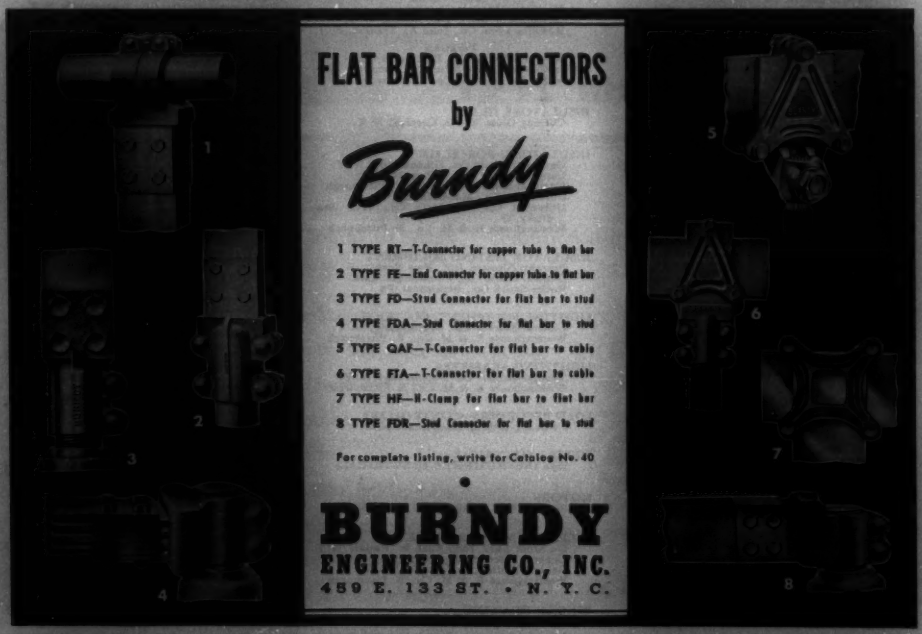

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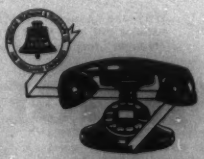

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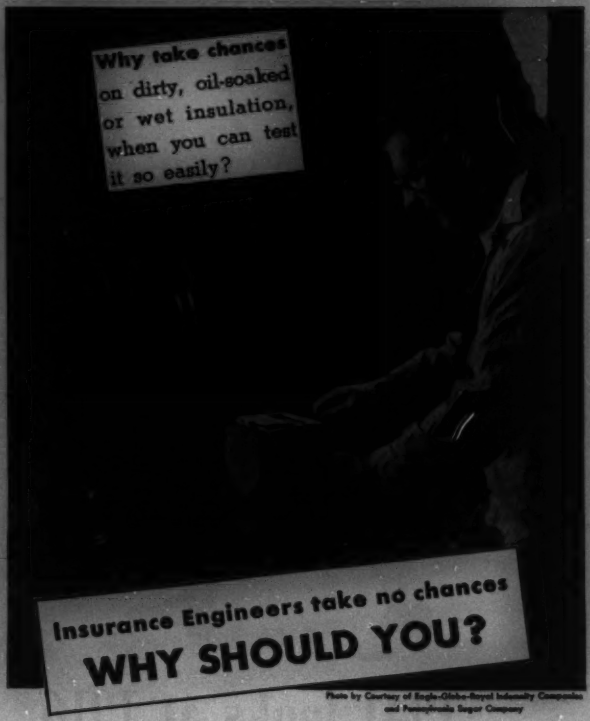
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Kuhlman CSP Transformer with one cover bushing, external de-ion gap and grounded secondary.

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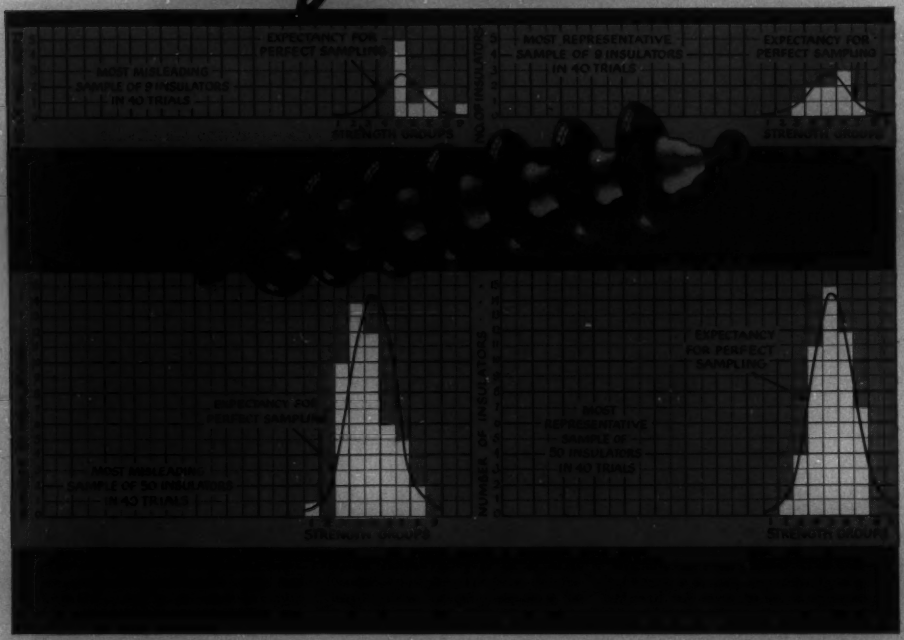
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